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SNOW AND THE THORNTHWAITE WATER BALANCE
IN A SUBARCTIC ENVIRONMENT

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE
OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF GEOGRAPHY

EDMONTON, ALBERTA

SPRING, 1969



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The undersigned certify that they have read,
and recommend to the Faculty of Graduate Studies
for acceptance, a thesis entitled "Snow and the
Thornthwaite Water Balance in a Subarctic Environ-
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fulfillment of the requirements for the degree of
Doctor of Philosophy.



ABSTRACT

The demand for water in North America is accelerating as a function of population increase plus the increased rate of water consumption per capita. Because the distribution of fresh-water does not coincide with the location of man, water supply problems have resulted.

The purpose of this thesis is to investigate some aspects of the hydrologic cycle in an area of surplus water so that the quantity and nature of this supply might be more fully understood. The general area selected for the study is the Subarctic; specifically, investigations were and are being conducted in the Yellowknife Area, N.W.T.

The thesis research is composed of two parts. First, a factor of the hydrologic cycle (snow precipitation) is intensively surveyed. Second, the snow data are related to other climatic-hydrologic factors by means of the Thornthwaite water balance concept.

The snow investigations were conducted within Pocket Lake basin, a sub-basin to Baker Creek. Area weighted, mean snow water equivalents are calculated from field maps and computer maps (SYMAPs). Characteristics are compared spatially and spring surplus patterns are deduced from maps of snow and water retention capacities. Snow depths, snow specific gravities, snowbank characteristics, and the basin melt pattern are illustrated and discussed.

The interrelation of snow data with other aspects of water is first attempted by using the unadjusted Thornthwaite procedure. Because of the low correlation of calculated runoff from Yellowknife Airport meteorological data with measured discharge from the Yellowknife River, adjustments to the procedure are attempted. Higher correlations with discharge are derived for variables expressing a delay between the time precipitation is received and the time streamflow materializes.

Based upon the foregoing information, numerous water balance equations are suggested for sites of differing retention capacities and for different seasons of the year. From these, it is demonstrated that several sites contribute more than twice the mean rate of surplus, while others contribute nothing, or even consume riparian waters.

Thus, water surplus patterns are presented spatially and by a series of equations for a select Subarctic area. The understanding of water supply in this portion of North America may play a significant role in water resources of the future.

ACKNOWLEDGEMENTS

This study was made possible by the cooperation of a number of people and organizations. I wish to express my gratitude for the financial assistance received from the Boreal Institute, University of Alberta, and the Baker Creek Project, International Hydrologic Decade, which facilitated the field work. The Miami University Computing Center (and especially Mr. Art Fiser) generously provided time which saved the writer's time exponentially.

Dr. Arleigh H. Laycock deserves special thanks for focusing the writer's attention on the aspects of water and, more specifically, for his constructive criticism during the process of writing. To the other members of the doctoral committee, Drs. Thomas Berg, Ian Campbell, Donald Gray, George Sitwell, and William Wonders, I extend my sincere appreciation for their involvement.

Assistance in the field was contributed by my colleagues Larry Stene and Wayne Moodie, also Ted Spence and Bruce Rains. Mrs. Carol Webb and Mrs. Marilyn Cromer made secretarial contributions; Harold Smith and Dan Sharp helped with some of the drafting of figures.

Finally, the role of my wife, Jan, has mainly been in absorbing the "low" points which tended to come home with me; the "highs" kept me working late at the office. Without her, the thesis would not be finished. The writer appreciates the encouragement offered by many others with whom he has had contact.

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CHAPTER I

INTRODUCTION AND APPROACH

Introduction

Water has commanded man's attention for probably as long as the term Homo sapiens can be applied. The long attention span has been maintained primarily because of the demands man makes on water. The biological demand is essential for life itself, but there are additional demands, such as agricultural and industrial supplies of water, domestic washing and waste disposal, or transportation and recreation activities.

As man increases in number and in sophistication, his demand for water grows by an increasing rate. Natural water supply, however, is subject to a different set of controls than is water demand, and thus, numerous regional imbalances have resulted between supply and demand. Water research derives most of its impetus from situations where a large demand is placed on a limited supply. Some solutions to such supply problems can be sought in other regions where supply exceeds local demand.

At present, the Subarctic is a region of excess water, but the quantities and characteristics of this supply are not well-known. It is toward a better evaluation of this Subarctic water supply that this thesis is directed.

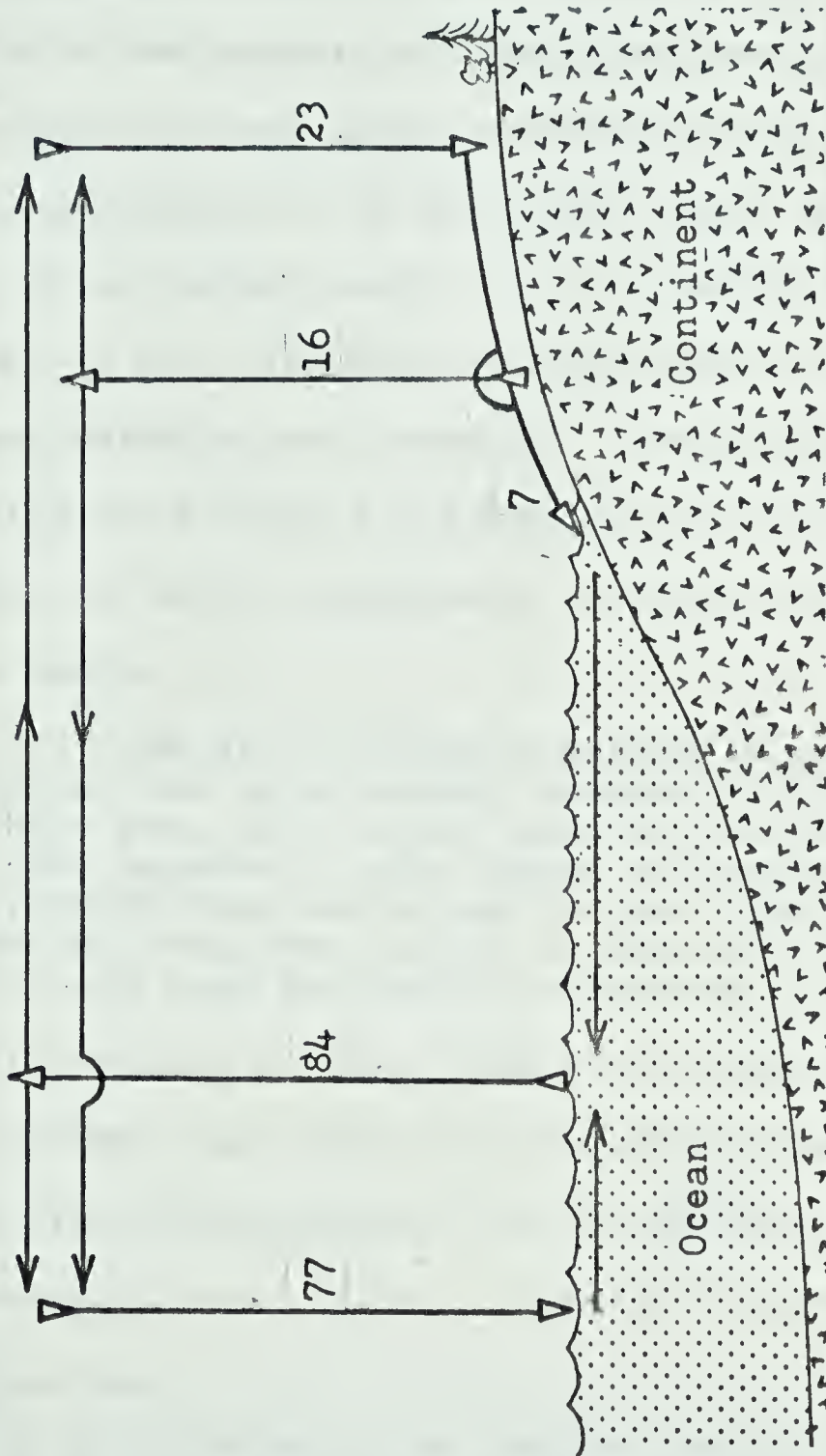
Evaluation first takes the form of testing a widely used empirical estimate of water surplus (i.e., the Thornthwaite water balance method) against measured discharge in the vicinity of Yellowknife, N.W.T. Because of the inaccurate estimates calculated from the Thornthwaite procedure, a distinctive factor of the Subarctic water environment (i.e., snow) is examined in detail with the purpose of modifying and improving the estimates of water supply in the Subarctic. Other adjustments of meteorological variables are also correlated with measured discharge in an attempt to develop a more significant predictor of annual water supply, and thus, suggest factors that should be investigated more fully in the future.

The Hydrologic Cycle

In studying water supply, it is important to know its patterns of movement over the earth's surface. The circulation of water is continuous, and the total amount of water retained by our planet is essentially constant. The hydrologic cycle is the conceptual model which has been used widely to illustrate the schematic circulation of the earth's waters. (See Figure 1-1.) The model summarizes the advection of water vapor through the atmosphere, a portion of which condenses and falls to earth as precipitation. Some of the received precipitation runs off the earth's surface as streamflow or as groundwater discharge and collects in the oceanic basins. Other waters on the moist land surface are evaporated or transpired by plants and thus are

THE HYDROLOGIC CYCLE

(100 units = mean annual global precipitation, 33.8 inches)



All Water	Approximate Distribution of <u>Fresh Water</u>			
97% = Oceans	75% = Ice Sheets and Glaciers	0.3% = Lakes		
3% = Other	14% = Groundwater (2,500'-12,500')	0.06% = Soil Moisture		
	11% = Groundwater (less than 2,500')	0.035% = Atmosphere		
		0.03% = Rivers		

Source of values, R.J. More, "Hydrologic Models and Geography," p.146; diagram modified.

Figure 1-1

transferred back to the air. The oceans provide even more effective evaporation sources which return large quantities of moisture back to the atmosphere and the cyclical circulation of water continues.

Several disciplines are involved in investigations dealing with the hydrologic cycle, however each discipline tends to have its own focus within the cycle. Regarding the field of hydrology, in an early but still basic text, R. K. Linsley, M. A. Kohler, and J. L. H. Paulhus state that "hydrology is most frequently interested in the relation between precipitation and runoff."¹ Recently, R. J. More concurred with this focus for hydrology, but also indicated the dependence of this relationship on other factors of the cycle when she wrote:

. . . One of the chief problems in hydrology is to define the relationship between rainfall 'input' and that part of 'output' represented by direct runoff, but because of the number of intervening factors, their complexity and the problems involved in measuring them, the nature of this relationship is still only very partially understood.²

Climatology's focus within the hydrologic cycle is directed toward the study of "the balance between the income of water from precipitation and the outflow of water by evapotranspiration. It is a climatic balance since quantities

¹R. K. Linsley, M. A. Kohler, and J. L. H. Paulhus, Applied Hydrology (New York: McGraw-Hill Book Company, Inc., 1949), p. 218.

²R. J. More, "Chapter Five, Hydrologic Models and Geography" in Models in Geography edited by R. J. Chorley and Peter Haggett (London: Methuen and Co., Ltd., 1967), p. 147.

[of] precipitation and evapotranspiration are active factors of climate."³

Other disciplines, such as oceanography, botany, soil science, and ecology, focus on yet other components of the general circulation.

The variations of the characteristics of the hydrologic cycle that are related to specific geographical regions (e.g., oceans or continents, low or high latitudes, urban or agricultural areas) are important problems. To explain these variations in light of their interrelationships with the other physical and human factors of the earth is the research frontier of geography. In a broader context, the discipline of geography is concerned with the "earth-wide man-environment system"⁴ as a general research frontier. The distinct geographical approach to this interdisciplinary problem is through the explanation of its spatial distributions. Therefore, the distribution of the variable character of the earth's waters is only one factor that can be studied by means of the geographical (i.e., spatial) approach.

Spatial research concerning the hydrologic cycle deals with: 1) the earthly distribution of the individual

³ C. W. Thornthwaite and J. R. Mather, Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance, Publications in Climatology, Vol. X, No. 3 (Centerton, New Jersey: Drexel Institute of Technology, Laboratory of Climatology, 1957), from Foreword.

⁴ E. A. Ackerman, "Where is a Research Frontier?" Annals of the Association of American Geographers, Vol. 53, No. 4 (December, 1963), p. 440.

characteristics, or 2) the integration of other environmental influences on water to explain its character at a particular place. "The movement of water over the land surface and within the unconsolidated surface mantle," E. A. Ackerman wrote, "display[s] definite alterations in value through the time scale here assumed as significant to distributional change, and . . . impinge[s] upon other processes which affect earth-space content."⁵ Therefore, he considers the investigation of water movement (i.e., the dynamic hydrologic cycle) to be "fundamental research."

Thornthwaite's Water Balance

The water balance is an approach to the study of the quantities of water moving through the hydrologic cycle. The water balance concept, as developed by C. W. Thornthwaite in the early 1940's, formed the basis for his widely cited 1948 article entitled "An Approach Toward a Rational Classification of Climate."⁶ The concept was succinctly described by Ackerman when he wrote:

The water balance of a given land area, land region or surface water body of the earth most simply stated is an input-output calculation of moisture

⁵ E. A. Ackerman, Geography as a Fundamental Research Discipline, Department of Geography Research Paper No. 53 (Chicago: The University of Chicago Press, 1958), p. 23.

⁶ C. W. Thornthwaite, "An Approach Toward a Rational Classification of Climate," Geographical Review, Vol. 38, No. 1 (January, 1948), pp. 55-94.

receipts, retention, and loss (expenditure, disappearance), over a given period of time.⁷

In application, a balance is calculated between incoming precipitation and outflows of stream and groundwater discharge, evaporation, and plant transpiration for a place through time. Also, there may be temporary additions to, or withdrawal from, the quantity of water stored within the region which must be considered. This balance of factors can be expressed by means of a formula that facilitates thought about the relationships involved. The formulaic expression of the water balance used in this thesis is

$$\text{Ppt} = (\text{PE} - \text{D}) + \text{Sur} \pm \text{SC} , \quad (1.1)$$

where: Ppt = precipitation,
 PE = potential evapotranspiration,
 D = deficit,
 Sur = surplus,
 SC = storage change.

A brief definition of each of these terms is:

Precipitation - rain, snow, and condensed-sublimated moisture that reaches the earth's surface from the atmosphere;

Potential evapotranspiration - the moisture lost by evaporation and transpiration under "optimum" moisture conditions (i.e., soil constantly at field capacity);

Deficit - the difference between optimum moisture demands (i.e., PE) and the amount of moisture that is actually available for evapotranspiration, (or that part of demand that cannot be supplied);

Surplus - the amount of incoming moisture (i.e., Ppt) that exceeds the demand (i.e., PE) when soil moisture retention is at field capacity to

⁷ E. A. Ackerman, "Foreword" to Three Water Balance Maps of Eastern North America, by C. W. Thornthwaite, J. R. Mather, and D. B. Carter (Washington: Resources for the Future, Inc., 1958), p. ii.

the root depth;

Storage change - the increase or decrease of moisture stored within the area either as lake and surface storage or as soil moisture retention storage.

The result of subtracting the deficit from the potential evapotranspiration (i.e., $PE - D$) equals the amount of moisture that is actually consumed through evaporation and transpiration, or the "actual evapotranspiration" (AE).

Importance of Water Balance Approach

The importance of the water balance as an approach to understanding the hydrologic cycle more fully can be indicated first by discussing the type of information that can theoretically be derived from it, and secondly, by citing a variety of publications that have made use of the water balance approach.

By knowing: 1) monthly precipitation totals, 2) the water retention capacity for the depth of rooting within the soil, and 3) measured or calculated⁸ values for monthly potential evapotranspiration for a place through time, it is a simple bookkeeping procedure to calculate monthly values for the other water balance variables in the formula. Through manipulation of the formula, focus can be directed toward

⁸ Thornthwaite developed a procedure for calculated potential evapotranspiration using the latitude and mean monthly air temperatures for a place. See either: Thornthwaite, "An Approach Toward A Rational Classification of Climate," pp. 55-94; or Thornthwaite and Mather, Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance, pp. 185-311.

water deficiencies, water surpluses, or changes in moisture stored. Also, by employing Thornthwaite's procedure for calculating⁹ potential evapotranspiration from other standard meteorological observations, attention can be directed toward potential evapotranspiration or resulting actual evapotranspiration. Therefore, besides its relevance to the geographical distribution of these factors, the water balance is applicable to both hydrology and climatology in that the focal points of each compose primary factors of the formula.

The water balance technique can also be: 1) used to estimate historical data that were not originally collected (e.g., runoff or evapotranspiration) if the necessary meteorological variables are available, 2) used to expand present limited networks of observations, and 3) adapted to any vegetation or soil condition by adjusting the value for soil moisture retention.

Since its appearance, the water balance approach has been widely used as an analytical tool. A variety of maps have been constructed from water balance calculations to portray the components spatially. Some examples of these include C. W. Thornthwaite, J. R. Mather, and D. B. Carter's¹⁰ series of three maps for eastern North America showing calculated potential evapotranspiration, water

⁹ibid.

¹⁰C. W. Thornthwaite, J. R. Mather, and D. B. Carter, Three Water Balance Maps of Eastern North America (Washington: Resources for the Future, Inc., 1958), maps in rear pocket.

deficit, and water surplus patterns. More recently, A. H. Laycock¹¹ presented water deficit and surplus maps for the Canadian Prairies, and M. E. Sanderson and D. W. Phillips¹² published maps of surplus patterns for Canada.

Several other qualities of the water balance have been utilized, such as its pedagogical values,¹³ or its convenience in estimating change in soil moisture as related to the timing of irrigation.¹⁴ Its widespread application as a descriptive technique of the active, water factor of climate stretches from Lake Maracaibo¹⁵ to Lake Erie¹⁶ and includes

¹¹A. H. Laycock, Water Deficiency and Surplus Patterns in the Prairie Provinces, Prairie Provinces Water Board Report No. 13 (Regina, Saskatchewan: Prairie Provinces Water Board, 1967), 92 pp. plus maps and appendices.

¹²M. E. Sanderson and D. W. Phillips, Average Annual Water Surplus In Canada, Climate Studies No. 9 (Toronto: Department of Transport, Meteorological Branch, 1967), 76 pp.

¹³See: A. N. Strahler, "Chapter Eight, Soil Water and the Water Balance," Introduction to Physical Geography (New York: John Wiley and Sons, Inc., 1965), pp. 117-127; or D. B. Carter, ed., Fresh Water Resources (Washington, D. C.: High School Geography Project of the Association of American Geographers, November, 1965), 160 pp.

¹⁴C. W. Thornthwaite, Climate and Scientific Irrigation in New Jersey, Publications in Climatology, Vol. VI, No. 1 (Centerton, N. J.: Drexel Institute of Technology, Laboratory of Climatology, 1953), pp. 1-8.

¹⁵D. B. Carter, The Water Balance of the Lake Maracaibo Basin During 1946-53, Publications in Climatology, Vol. VIII, No. 3 (Centerton, N. J.: Drexel Institute of Technology, Laboratory of Climatology, 1955), pp. 205-227.

¹⁶M. E. Sanderson, A Climatic Water Balance of the Lake Erie Basin 1958-1963, Publications in Climatology, Vol. XIX, No. 1 (Centerton, N. J.: C. W. Thornthwaite Associates, Laboratory of Climatology, 1966), pp. 1-87.

most of the continents¹⁷ of the world, plus general coverage of the earth as a whole.¹⁸

Statement of Problem

Previous Tests of Water Balance

With all of its versatility and its application to widespread areas, the water balance has become a popular research technique. However, the writer considers it important that the accuracy of this approach be understood for the areas to which it is being applied.

Tests of the Thornthwaite water balance have been conducted for mid-latitude locations. In 1955, Thornthwaite and Mather wrote that:

Since the moisture surplus as computed from the bookkeeping procedure represents water that is available for streamflow it is possible to obtain estimates of this latter parameter from climatic data alone. Thus, the procedure enables one to determine streamflow in areas where no stream gage records exist. If such records are available the information can be used as a check on the validity of the bookkeeping approach. . . . A map of average annual surplus water over eastern United States as computed from the water balance procedure [is compared to] a map of the same region showing the average annual measured runoff from gaged streams. The first map was prepared entirely from climatic data while the

¹⁷ See the recent series edited by J. R. Mather, Average Climatic Water Balance Data of the Continents, Publications in Climatology (Centerton, N. J.: C. W. Thornthwaite Associates, Laboratory of Climatology).

¹⁸ T. E. A. Von Hylckama, The Water Balance of the Earth, Publications in Climatology, Vol. IX, No. 2, (Centerton, N. J.: Drexel Institute of Technology, Laboratory of Climatology, 1956), pp. 59-117.

second was drawn from the many measurements of stream-flow made by the U. S. Geological Survey. These maps are sufficiently alike that one could be substituted for the other without loss.¹⁹

Thornthwaite and Mather continued to cite locations that illustrate the accuracy with which calculated water balance surplus estimates measured discharge. For Arizona, an arid region, it was found that "the agreement clearly indicates the utility of the method of computing stream runoff from climatic data."²⁰ For the Coshocton area in Ohio, they reported that "monthly and annual computed values of runoff are . . . in good agreement with measured values . . . and the average values . . . based on the series of years investigated are almost identical."²¹ Throughout the Tennessee River Basin, Thornthwaite and Mather found "excellent"²² agreement of mean annual values, and using thirty-seven years of data in Virginia, they reported "close agreement"²³ of annual values of measured and computed runoff plus close agreement of the seasonal course of measured and calculated runoff.

In another article Thornthwaite, Mather, and Carter wrote that calculated "water surplus is equal to [measured]

¹⁹C. W. Thornthwaite and J. R. Mather, The Water Balance, Publications in Climatology, Vol. VIII, No. 1 (Centerton, N. J.: Drexel Institute of Technology, Laboratory of Climatology, 1955), p. 48.

²⁰Ibid., p. 49.

²¹Ibid.

²²Ibid., p. 51.

²³Ibid., p. 52.

streamflow in its yearly total, and with the consideration of local conditions the seasonal pattern of runoff from the computed surplus will approximate the actual measured value."²⁴ More precisely, Sanderson recently derived a correlation coefficient of .995²⁵ between water surplus as calculated by the Thornthwaite method and measured discharge from fifteen drainage basins in southern Ontario for the water year 1959-60, and concluded that "this excellent correlation was obtained in spite of the varied glacial topography and soils in the area."²⁶ Phillips²⁷ obtained a .86 correlation coefficient between computed annual water surplus for one meteorological station and discharge measured from seven nearby drainage basins in southwestern Ontario.

High Latitude Test

In 1948, Thornthwaite concluded that "this classification can be improved. A first step will be to develop better means of determining potential evapotranspiration. Additional observations are needed, particularly in the tropics and

²⁴Thornthwaite, Mather, and Carter, Three Water Balance Maps of Eastern North America, p. 27.

²⁵Sanderson, A Climatic Water Balance of the Lake Erie Basin 1958-1963, p. 17.

²⁶Ibid.

²⁷D. W. Phillips, "Estimating Runoff of River Basins in Southwestern Ontario," unpublished paper delivered at the East Lakes divisional meeting of the Association of American Geographers held at the University of Windsor on October 20, 1967.

high latitudes."²⁸

Some studies of "high latitude" water balance characteristics have been conducted (see Review of Pertinent Literature in this chapter), but thus far, no significant evaluation of water supply relationships or modifications of the Thornthwaite water balance estimates have resulted. Therefore, the writer feels that it is important to evaluate and attempt to modify the Thornthwaite procedure for Subarctic conditions for two reasons: 1) because the Thornthwaite technique, without modification, is being applied to high latitude situations as part of the continental survey of the water balance,²⁹ and 2) because of the importance of the water factor to high latitudes as a local resource (or with export³⁰ values) and as a dominant factor of the physical environment.

As a high latitude test of the Thornthwaite water balance, annual gauged discharges from the Yellowknife River were compared to calculated annual surplus values using the

²⁸ Thornthwaite, "An Approach Toward A Rational Classification of Climate," p. 88.

²⁹ For example, see: J. R. Mather, ed., Average Climatic Water Balance Data of the Continents, Part VI: North America (excluding United States), Publications in Climatology, Vol. XVII, No. 2 (Centerton, N. J.: C. W. Thornthwaite Associates, Laboratory of Climatology, 1964), pp. 235-414.

³⁰ A. H. Laycock, "The Rationale of Water Export and Its Implications for Water Resources Research in the North," unpublished paper delivered at the 2nd Northern Resources Research Conference held in Whitehorse, Yukon Territory, on August 20, 1968.

Yellowknife Airport meteorological station data and the Thornthwaite water balance technique. Twenty-five years of comparable record (1942-43 through 1966-67) were available for this high latitude ($62^{\circ} 28' \text{ N.}$) location in the Canadian Northwest Territories. The observations and calculations are discussed fully in chapter IV, but it is important here to mention that the simple correlation coefficient between the measured discharge and calculated surplus was found to be .160, which is not statistically significant at the 5 per cent level.³¹

In view of such high correlations between measured discharge and computed surplus using the Thornthwaite water balance throughout diverse, mid-latitude areas previously cited, it is felt by the writer that the low correlation of these factors for the Yellowknife Area³² suggests doubt as to the applicability of this technique to high latitude locations. Therefore, the basis of the present research is the investigation into the reasons why the Thornthwaite water balance without modifications is not suitable to the Yellowknife Area.

³¹At the 1 per cent level of statistical significance with D.F. = 23 (or N-2), the simple correlation coefficient must be equal to or greater than .505; at the 5 per cent level of significance it must be .396 or more.

³²The "Yellowknife Area" will be defined more specifically in chapter II of this thesis.

Possible Causes of Error

To the writer, there appear to be several factors that could be causing the inapplicability of the Thornthwaite water balance to the Yellowknife Area. One of these is the possibility that the Thornthwaite method of calculating the potential evapotranspiration has not been adjusted adequately for high latitude situations. As stated previously, Thornthwaite recognized this possibility and suggested that his formula could be revised, specifically mentioning improvement in the means of determining high latitude potential evapotranspiration.³³

As the formula presently stands, potential evapotranspiration is adjusted for duration of sunlight as determined from the date and latitude of the station, but this adjustment only varies from the Equator to 50° N. or S. latitude, and "poleward from 50° [one should] use the duration of sunlight factors for 50°."³⁴ More recently, it has been discovered that:

. . . the temperature of the air is an indication of the amount of net radiation devoted to heating of the air [as opposed to heating the ground or supplying the latent heat of vaporization]. Recent observations show that the ratio of the energy used for heating of the air to the energy devoted to evaporation varies with temperature. This fact was discovered empirically and although not understood at

³³Thornthwaite, "An Approach Toward A Rational Classification of Climate," p. 88.

³⁴Thornthwaite and Mather, Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance, p. 227.

the time was a basic element of the equation. In 1948, when Thornthwaite presented a classification of climate based on the water balance, the hope was expressed that a more rational method would be developed to determine potential evapotranspiration. In the ensuing decade several methods have been presented, among which those of Penman, Blaney and Criddle, Halstead, and Mather may be mentioned. However, no method has yet been developed which is an improvement on the original equation, although one is still being sought.³⁵

Since the "ratio" does vary with temperature and "recent measurements have shown that only 20-60 per cent [of net radiation] goes into the evaporation from moist soils in Point Barrow, Alaska, whereas 80-90 per cent are utilized for evaporation in Centerton, New Jersey,"³⁶ it seems that some adjustments of the calculation of potential evapotranspiration should be made for the radiation conditions of latitudes higher than 50°.

The second possible error could be that the mean monthly potential evapotranspiration calculations do not approximate other meteorological conditions for high latitudes as accurately as they do for mid-latitudes. To elaborate, the Thornthwaite calculation of potential evapotranspiration is simplified to average monthly conditions, and thereby it does not consider the actual, short-term variations of wind, cloud cover-sunshine, or humidity. The Thornthwaite calculations therefore were based on the premise

³⁵Thornthwaite, Mather, and Carter, Three Water Balance Maps of Eastern North America, pp. 6-7.

³⁶Ibid., p. 4.

that these variations average out when considering a monthly time period. This is rather accurate for many mid-latitude situations, whereas the short evapotranspiration season in high latitudes may be characterized by such conditions as "sunny" or "cloudy" months, "windy" or "calm" months, or high or low humidity for a month at a time. Therefore, the actual conditions could vary considerably from some "average" value and cause a corresponding variance in evapotranspiration.

The third possible error deals with a factor of the hydrologic cycle which is more distinctly a characteristic of high latitudes than of middle or low latitudes. The factor is the snow portion of precipitation, and the fact that the snow cover accumulates and persists for about one-half the year. Snow precipitation could lead to erroneous water balance calculations because of: 1) inaccurate point measurement at the time of snowfall or, 2) spatial relocation by means of drifting of the accumulating snow cover.

The rapid decrease in accuracy of rain catch and, more severely, of snow by standard gauges as wind speed increases has been widely reported.³⁷ During winds of fifteen miles per hour, W. T. Wilson suggested that, on the average, less than 75 per cent of rain precipitation is recorded by standard

³⁷For a summarizing graph, see: W. T. Wilson, "Discussion" [of "Precipitation at Barrow, Alaska, Greater Than Recorded" by R. F. Black, Transactions of American Geophysical Union, Vol. 35, No. 2 (April, 1954), pp. 203-206], Transactions of American Geophysical Union, Vol. 35, No. 2 (April, 1954), pp. 206-207.

gauges and that only about 50 per cent of snow is caught.³⁸ In an Arctic environment, R. F. Black estimated that snowfall was two to four times that recorded by the U. S. Weather Bureau station at Barrow, Alaska.³⁹ He based his estimates on snow depth-density measures and, indirectly, from observations of moisture content of the active layer through the summer, plus noting consistent summer runoff and other field observations. Wilson, in his "Discussion" of Black's paper, did not disagree with Black's estimates of much greater precipitation at Barrow.

When considering all of the factors of the water balance, point measurements of snowfall are of limited value. Snow precipitation can be relocated by drifting over the land surface before it is converted by melting into an "active" factor of the water balance. The term "active" as it is used here means that water, and not snow, is in a physical state which can be used dynamically by plants and transpired, can contribute to runoff or soil moisture recharge, and can be evaporated readily. (It is possible for snow to enter into the activity of the water balance through sublimation, however this is very limited quantitatively.) Therefore, it is the distribution of snow on the land at the time of melt which is pertinent to such factors as surplus or soil moisture. Where

³⁸Ibid., p. 207.

³⁹R. F. Black, "Precipitation at Barrow, Alaska, Greater Than Recorded," Transactions of the American Geophysical Union, Vol. 35, No. 2 (April, 1954), p. 206.

the snow has accumulated in large drifts, there is effectively a large supply of detained moisture; where the snow cover has been degraded by wind action, there is effectively a small amount of winter precipitation. Thus, the areal distribution of the basic winter input (snow precipitation) to the water balance can deviate substantially from even the most accurate point measurements at the time of fall. In the Thornthwaite water balance, no consideration is given to either erroneous snowfall measurements or the effects of drifting snow.

Permafrost is an additional element that is distinctive to high latitudes and influences the water balance. Its effect of delaying the annual runoff peak in the Subarctic of western Canada has been suggested by A. Sommer and E. S. Spence.⁴⁰ Another factor that could be influencing the character of the Yellowknife Area water supply is the large proportion of surface area covered by lakes and poorly drained basins. These too, could have a delaying effect on streamflow.

There are numerous other factors that might be influencing the flow regimes and contributing to the lack of correlation between calculated runoff by the Thornthwaite method and measured discharge. For example: 1) the meteorological measurements made at the Yellowknife Airport may not be representative of the entire Yellowknife River drainage basin for which the discharge measurements are made, 2) albedo values in

⁴⁰ A. Sommer and E. S. Spence, "Some Runoff Patterns in a Permafrost Area of Northern Canada," The Albertan Geographer, No. 4 (April, 1968), pp. 60-64.

the Yellowknife Area may be quite dissimilar to those in the mid-latitudes because of the higher proportion of water surfaces and limited vegetation-cover, and 3) the existing vegetation may be consuming available water at different rates from those of mid-latitude flora because of adaptations to local conditions.

Direction of Present Research

In this paper, the writer has investigated the thesis that aspects of snow contribute a significant portion of the error that results when applying Thornthwaite's water balance technique to the Yellowknife Area, N.W.T. The first part of the paper, therefore, involves the characteristics of snow as a component of the Yellowknife water balance. According to J. Amorocho and W. E. Hart's subdivision of hydrology, this portion could be considered "physical hydrology"⁴¹ in that it:

. . . espouses the pursuit of scientific research into basic operations of each component of the hydrologic cycle in order to gain a full understanding of their mechanisms and interactions. Although the immediate motivation of an individual researcher may not transcend the narrow confines of a set of special phenomena, it is implicit that a full synthesis of the hydrologic cycle may eventually be sought. This concept of a full synthesis is held to be the only rational approach to hydrology.⁴²

Specifically, the location and general physical

⁴¹J. Amorocho and W. E. Hart, "A Critique of Current Methods in Hydrologic Systems Investigations," Transactions of the American Geophysical Union, Vol. 45, No. 3 (June, 1964), p. 308.

⁴²Ibid., p. 307.

environmental features of the study area are discussed to provide background information. In the third chapter, the problems of accurate snow measurement at a point and for an area are examined, and the results of the field work carried out in the small Pocket Lake basin near Yellowknife are presented. After a brief discussion of the SYMAP technique (a computer mapping program), a series of computer maps portraying the water equivalents of snow, the snow depth, and the specific gravity of the snow cover for spring 1967 and 1968 are introduced and the distributions discussed. Calculations are made from the mapped data, and the snow distribution is related to estimated retention values for the basin to provide information on the generation of water surpluses. A series of photographs taken from the air is used to illustrate the melting pattern of the snow cover in Pocket Lake basin through the spring 1967 season. Detailed investigations of melt in several snowbanks are presented.

The latter portion of the thesis could be considered "systems hydrology"⁴³ according to Amorocho and Hart's division, in that attention is given to the available measurements of "observable variables in the hydrologic cycle which appear pertinent to the problem," but that "the vast complexity of the knowledge now available and the knowledge likely to exist in the foreseeable future, make the possibility of a full synthesis so remote . . . that it must be discarded for practical

⁴³Ibid., p. 308.

purposes."⁴⁴ The Thornthwaite water balance is used as the "systems" approach by which measured and calculated values are manipulated to derive other estimated values for the Yellowknife Area.

Specifically, the discharge records for the Yellowknife River basin are presented in Chapter IV, along with the Thornthwaite water balance values which were calculated on a monthly basis for the water years of 1942-43 through 1966-67. The Thornthwaite "systems" prediction of annual water year surplus is correlated with measured discharge. Because the correlation is not significant, some modifications of the Thornthwaite calculations are presented, one of which involves the snow adjustments that were developed for Pocket Lake basin. Other measures of meteorological variables are correlated with measured discharge in an attempt to derive a more accurate predictor of annual water supplies in the Yellowknife Area. Through this correlation analysis the importance of other factors to discharge patterns is suggested, and these relationships are used to indicate meaningful prospects for future research into water supply patterns of the Subarctic.

The dependence of hydrologic systems analysis on the information supplied by physical hydrology is undeniable, especially regarding the choice of variables considered, refinement of relationships obtained, and extent of the linkage

⁴⁴Ibid., p. 307

developed in the systems. The structure of this thesis is built on the detailed investigations of one physical component, plus the consideration of others, for a Subarctic milieu with the prospect of refining a widely used systems technique.

The resulting work can be considered geographical research because it involves the investigation of a spatially variable factor of the earth (i.e., water supply) in a problematical region of the world, thus clarifying the understanding of the world distribution of a systematic geographic factor. Also, the examination of the spatial character of the snow cover and the interpretation of the interrelationships of the physical environmental factors to the water balance involve the use of geographical research techniques.

Review of Pertinent Literature

In addition to the references previously cited, there are several additional studies that pertain to the water balance of the North American high latitudes. Three early investigations were published by Sanderson. One was a general application of the Thornthwaite climatic classification to all of Canada⁴⁵ in which she mentioned Thornthwaite's uncertainty as to the applicability of his calculated potential evapotranspiration to "polar regions." She suggests, however, that even without extensive measurements, there is evidence that

⁴⁵M. E. Sanderson, "The Climate of Canada According to the New Thornthwaite Classification," Scientific Agriculture, Vol. 28, No. 11 (November, 1948), pp. 501-517.

the values are of the "right order of magnitude" for Canada. Using the available, long-term mean values, she mapped a deficit of at least four inches and a very limited surplus (i.e., centrally located in the zero to two inch annual surplus class) for the Yellowknife Area.

In a second article which dealt more specifically with Canada's Northwest,⁴⁶ Sanderson discussed vegetation, soil, crop experimentation, streamflow, and the calculated Thornthwaite water balance as factors that indicate drought conditions within the Mackenzie Valley. She again mapped a deficit for Yellowknife of between four and five inches annually. Commenting on Sanderson's article, A. H. Clark inferred that since the observed wet conditions of the northern muskeg in summer are related to poor drainage, they must be a "legacy from Pleistocene glaciation rather than attributable to abnormally low evaporation."⁴⁷ Of course, the poor drainage caused by the presence of permafrost, the possibility of greater annual precipitation totals than are measured at the northern meteorological stations, and the reduced rate of moisture use by local plants which are adapted to limited supplies, could also be contributing to muskeg conditions.

The third article by Sanderson dealt with the

⁴⁶ M. E. Sanderson, "Drought in the Canadian Northwest," Geographical Review, Vol. 38, No. 2 (April, 1948), pp. 289-299.

⁴⁷ A. H. Clark, "Contributions to Geographical Knowledge of Canada Since 1945," Geographical Review, Vol. 40, No. 2 (April, 1950), p. 294.

experimental measurement of potential evapotranspiration at Norman Wells⁴⁸ as a field check of her statement about drought and also the validity of extending the Thornthwaite equation for calculating potential evapotranspiration north of 50° latitude. Using an evapotranspirometer sown to Kentucky bluegrass, she concluded that her seasonal measurements (i.e., sixty-two days) of potential evapotranspiration were "almost the same" as the Thornthwaite calculated values for Norman Wells.

More recently, in connection with his permafrost investigations, R. J. E. Brown found that the type of vegetation planted in the evapotranspirometer at Norman Wells appeared to affect the rate of potential evapotranspiration. Using a series of measuring devices at five sites, each site having a different type of vegetative cover, he concluded that "potential evapotranspiration rates were significantly higher through the Kentucky bluegrass at the Thornthwaite Site than through the sedge, moss, and lichen at other sites."⁴⁹

The Point Barrow, Alaska,⁵⁰ heat and moisture balance

⁴⁸M. E. Sanderson, "Measuring Potential Evapotranspiration at Norman Wells, 1949," Geographical Review, Vol. 40, No. 4 (October, 1950), pp. 636-645.

⁴⁹R. J. E. Brown, "Potential Evapotranspiration and Evaporation Observations at Norman Wells, N.W.T.," Proceedings of Hydrology Symposium No. 2: Evaporation (Ottawa: Queen's Printer and Controller of Stationery, 1965), p. 124.

⁵⁰J. R. Mather and C. W. Thornthwaite, Microclimatic Investigations at Point Barrow, Alaska, 1956, Publication in Climatology, Vol. IX, No. 1 (Centerton, N. J.: Drexel Institute of Technology, Laboratory of Climatology, 1956), pp. 1-51; and J. R. Mather and C. W. Thornthwaite, Microclimatic Investigations at Point Barrow, Alaska, 1957-1958, Publications

studies were conducted by the Laboratory of Climatology during the years 1956 through 1958. In addition to testing various instruments, two pertinent conclusions were drawn. First, with conditions approximating potential evapotranspiration, it was found that "the evaporative heat flux is about 40 per cent of the net radiation. . . . We assume that the lower evaporation is related to the occurrence of permafrost. The reason for the different rate of utilization of net radiation between mid-latitudes and the Arctic region needs to be investigated more fully,"⁵¹ Secondly, the measurements of precipitation and potential evapotranspiration with indigenous vegetation for "all three years indicate a virtual balance between the precipitation and the evapotranspiration during the summer period in the Barrow area."⁵²

G. S. Cavadias⁵³ presented a general study of moisture surplus for Canada with specific reference to the application of Thornthwaite's water balance approach to some Subarctic watersheds in Quebec. Using only mean annual temperature and precipitation data to calculate evapotranspiration and

in Climatology, Vol. XI, No. 2 (Centerton, N. J.: Drexel Institute of Technology, Laboratory of Climatology, 1958), pp. 59-239.

⁵¹Mather and Thornthwaite, Microclimatic Investigations at Point Barrow, Alaska, 1957-1958, p. 88.

⁵²Ibid., p. 98.

⁵³G. S. Cavadias, "Evaporation Applications in Watershed Yield Determination," Proceedings of Hydrology Symposium No. 2: Evaporation (Ottawa: Queen's Printer and Controller of Stationery, 1965), pp. 170-178.

comparing the resulting surplus with measured streamflow in Quebec, he concluded "that Thornthwaite's water balance method tends to overestimate evapotranspiration losses in the region under consideration."

L. V. Brandon⁵⁴ discussed generally the groundwater and graphed the measured stream discharge for the Yellowknife Area as a portion of the Mackenzie drainage. Although the topic of this Report is quite relevant to the present paper, Brandon's focus was on the presentation of measured discharge records. Since these measurements were (and still are) available for such a small proportion of the area Brandon considered, and of the North in general, the application of his Report is limited.

Reasons for Selecting Area and Topic

The reasons that influence the direction in which one chooses to work are sometimes difficult to specify. Concerning the selection of a problem to investigate in pure research, E. B. Wilson wrote:

One of the most important criteria is this: it should interest the investigator strongly. Scientific research, not being a routine process but requiring originality and creative thought, is very sensitive to the psychological state of the scientist.

⁵⁴L. V. Brandon, Groundwater Hydrology and Water Supply in the District of Mackenzie, Yukon Territory, and Adjoining Parts of British Columbia, Paper 64-39 of the Geological Survey of Canada, Department of Mines and Technical Surveys (Ottawa: Queen's Printer and Controller of Stationery, 1965), 102 pp.

An uninterested worker is unlikely to produce the new ideas necessary for progress.⁵⁵

It is possible, however, to mention several reasons, in addition to "interest," that have contributed to the choice of the present research regarding the area and topic involved.

The Yellowknife Area provides a typical physical setting regarding climatic, terrain, and vegetational factors for a much larger and relatively homogeneous region of northwestern Canada; therefore, findings can be extended in areal application. Also, streamflow and meteorological data for the Area are available for a long and comparable period. Yellowknife is readily accessible from Edmonton, Alberta, by airplane and presently forms the northernmost focal point of the all-weather⁵⁶ Mackenzie Highway, which allowed the writer to make many trips into the study area.

With regard to the selection of the topic of investigation, the writer felt that the quantity of annual water supply for the Area was of primary importance. In attempting to apply the water balance technique of estimating water supply, errors were encountered and the snow factors were selected for special attention because of their pertinence to northern waters. Investigations into the potential

⁵⁵E. B. Wilson, Jr., An Introduction to Scientific Research (New York: McGraw-Hill Book Company, Inc., 1952), p. 1.

⁵⁶The highway is all-weather, but traffic into Yellowknife is prohibited for about a month in the fall when the formation of ice on the Mackenzie River halts the summer ferry and for another month in the spring during the breakup of the winter ice bridge.

evapotranspiration factors of the Yellowknife Area would have involved more elaborate equipment and longer periods of data collection than were available to the writer.

Snow, as opposed to rain, is more easily measured on an areal basis because most of the winter's fall is retained on the land surface in spring, whereas rain is mobile at the time of fall. Also, the "snow cover is more heterogeneous than [rain] precipitation"⁵⁷ and therefore, requires more intensive investigation in order that the accurate distributions of water equivalents be understood.

Finally, with more numerous statements being made about elaborate schemes to utilize excess northern water in various parts of North America, it seems important to more fully evaluate the water supply of the North so that utilization plans can be soundly based. One recent article that appeared in Yellowknife's weekly newspaper suggested some prevailing feelings when it reported that "one-third of the fresh-water on the North American continent is in the Northwest Territories, and 93 thirsty Americans were here to look at it last week."⁵⁸

⁵⁷ Secretariat of the Canadian National Committee, International Hydrologic Decade, Guide Lines For Research Basin Studies (Ottawa: National Research Council of Canada, International Hydrologic Decade, Canadian National Committee, February, 1966), p. 3.

⁵⁸ "Americans View Our Water," News of the North (Yellowknife, N.W.T.), June 27, 1968, pages not numbered.

CHAPTER II

PHYSICAL SETTING OF YELLOWKNIFE

Introduction

The movement of water through the various phases of the hydrologic cycle is greatly influenced by the physical environmental factors of the Yellowknife, N.W.T., Area. Being Subarctic in character, it is dominated by a severe winter, yet mild summer, climate. Other elements of the environment that influence the nature of water include the glacially eroded, Canadian Shield terrain, the thin soil mantle, permafrost conditions in soil and bedrock, and the restricted vegetational development. Each of these factors will be discussed and its pertinence to the water balance of the locale elucidated, but first the location of the study area is presented.

Location

The community of Yellowknife, the new capital of Canada's Northwest Territories, is located in the south-central portion of the District of Mackenzie, N.W.T. The settlement is focused around the intersection of the $62^{\circ} 27'$ North latitude line and the $114^{\circ} 22'$ West longitude line. (See Map 2-1.) This is approximately 275 miles south of the Arctic Circle and slightly more than 600 air miles (or 1000

MAP 2-1
MACKENZIE RIVER DRAINAGE BASIN

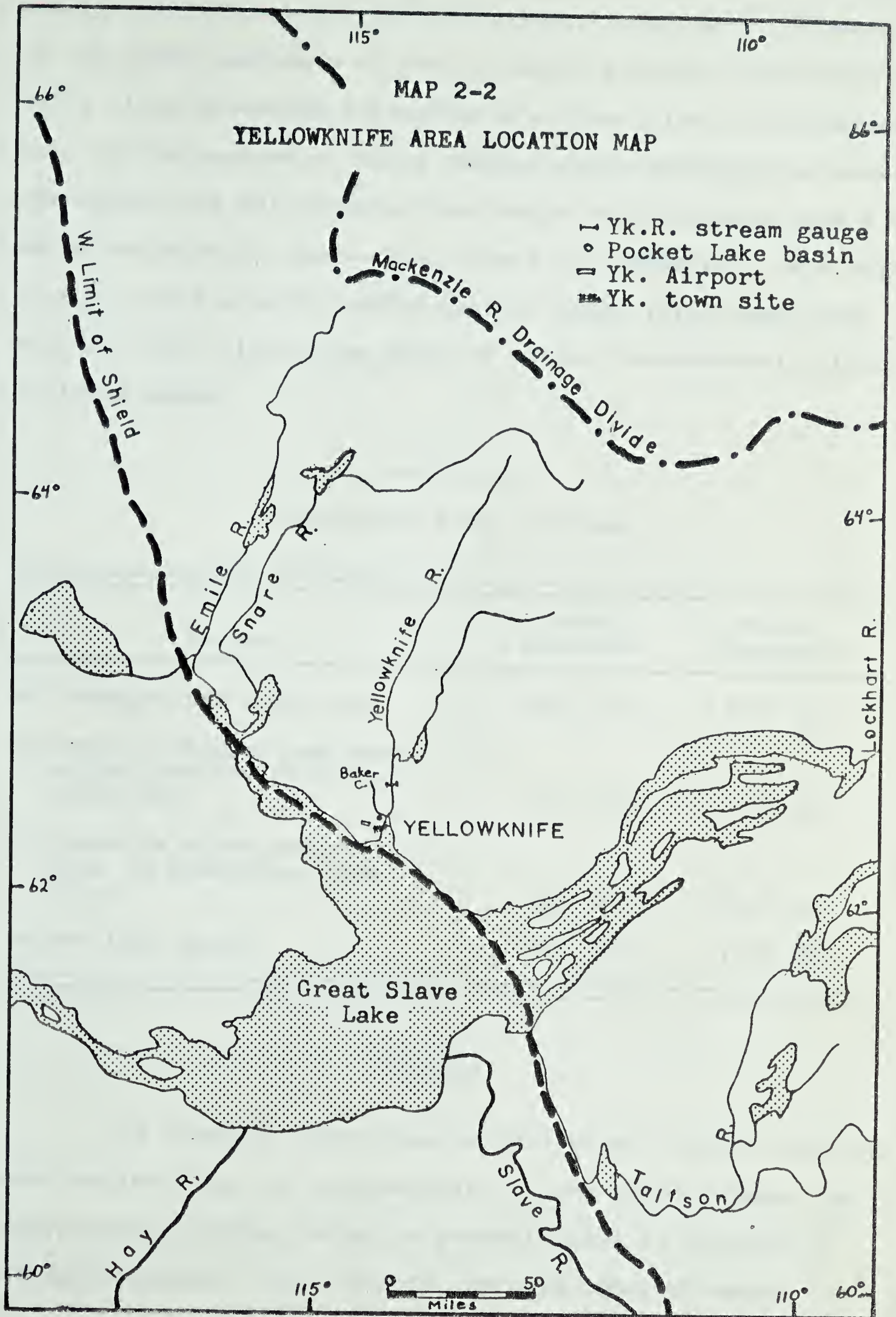


highway miles) north of Edmonton, Alberta, the nearest major city. Longitudinally, Yellowknife is 4° east of Los Angeles, California.

Yellowknife is situated on the north shore of Great Slave Lake which occupies a portion of the Mackenzie River basin. Yellowknife Bay is a small embayment of the North Arm of Great Slave Lake. The Bay terminates at the mouth of Yellowknife River and provides a harbor for the capital settlement located on its western shore.

The Mackenzie River is the major drainage system of western Canada. Its drainage basin stretches from the southern boundary of the Peace River and Athabasca River basins in central Alberta to its delta at the Arctic Ocean. The Mackenzie drainage basin includes the "northern Great Lakes" of Lake Athabasca, Great Slave Lake, and Great Bear Lake. (See Map 2-1.) The streams which drain into Great Slave Lake from the north and east are relatively short streams draining a series of small basins developed in the Shield bedrock and are therefore in marked contrast to the major river systems composing most of the Mackenzie River basin.

For the purpose of this thesis, the phrase "Yellowknife Area" applies to the region from which primary data have been collected. The precise locations of all the data collection points used in the thesis are listed in Table II-1 and located on Map 2-2. Most of the data originates from the meteorological station at the Yellowknife Airport



and from field work in the nearby Baker Creek basin (especially the small sub-basin of Pocket Lake); however, the Yellowknife River discharge measurements at the inlet to Prosperous Lake are indicative of water balance relationships that occur throughout the Yellowknife River basin which extends some 150 miles north of the town site. The Area, therefore, is a portion of the glacially eroded Shield region lying north and east of Great Slave Lake which is within the Mackenzie River drainage basin.

TABLE II-I
YELLOWKNIFE AREA LOCATIONS

Places	North Latitude	West Longitude
Yellowknife new town site	62° 27'	114° 22'
Yellowknife Airport meteorological station (682 feet elevation)	62° 28'	114° 27'
Yellowknife River gauge at inlet to Prosperous Lake (7SB ₃)	62° 40'	114° 16'
Pocket Lake basin	62° 30'	114° 22'

Climate

The climatic conditions of this high latitude location are pertinent to the consideration of the water balance for two reasons. First, water in several forms is actually a climatic element, and secondly, because other climatic

elements strongly affect the character of water in both meteorological and hydrological forms. Only a general discussion of such climatic factors as temperature, precipitation, sunshine, and winds is presented here to provide fundamental background from which the detailed consideration of the water balance elements will later be made.

Temperature

Latitudinal Control. Temperature is largely determined by latitude. Yellowknife's high latitudinal location results in major seasonal variations in the amount of insolation received at the ground surface. This is caused by the pronounced change with seasons of the relationships of three factors governing the receipt of solar radiation at the earth's surface.

The first of these factors is the number of hours per day that the sun is above the horizon; thus, it is the factor governing the potential receipt of incoming solar radiation. For the Yellowknife Area (approximately $62\frac{1}{2}^{\circ}$ N.) the possible duration of sunshine varies greatly from winter to summer with the extremes occurring on the dates of the solstices. The potential duration of sunshine for the winter solstice is four hours and fifty-five minutes; for the summer solstice it is twenty hours and one minute.¹

¹ Smithsonian Institution, Smithsonian Meteorological Tables, Smithsonian Miscellaneous Collections, Vol. 86 (5th rev. ed.; Washington: The Smithsonian Institution, 1931), pp. 211-222.

The second factor pertains to how directly the incoming solar radiation is received by the earth's surface. Figure 2-1 diagrammatically illustrates the angle at which the noon solar rays will intersect the earth's surface on the solstices and equinoxes at Yellowknife's latitude. The more nearly perpendicular angle of solar radiation in summer results in more intensive heating of any given unit area of the earth's surface than does the lower angle in winter.

A third factor of temperature results from latitudinal position and involves the thickness of the atmosphere through which solar radiation must penetrate before it reaches the ground. For any given latitude, the length of passage through the atmosphere varies according to the angle the incoming rays make with the horizon. That is, when the angle is small (winter), the depth of atmosphere is large; when the angle is more nearly perpendicular (summer), the passage is short. Since the major effect of the atmospheric gases on incoming radiation is to decrease it by means of reflection, scatter, and absorption, the radiation is greatly reduced by the lengthy winter passage, while the more direct summer radiation is less severely reduced.

The effects of these three factors on temperatures (i.e., length of daylight, angle of insolation, and depth of atmosphere) combine synergistically to produce an extreme annual fluctuation of temperatures. For example, in summer the daylight periods are longest, the angle between the horizon and the incoming solar radiation is the greatest, and

ANGLE OF MID-DAY SUN ABOVE HORIZON FOR YELLOWKNIFE, $62^{\circ}27'$ N. LATITUDE

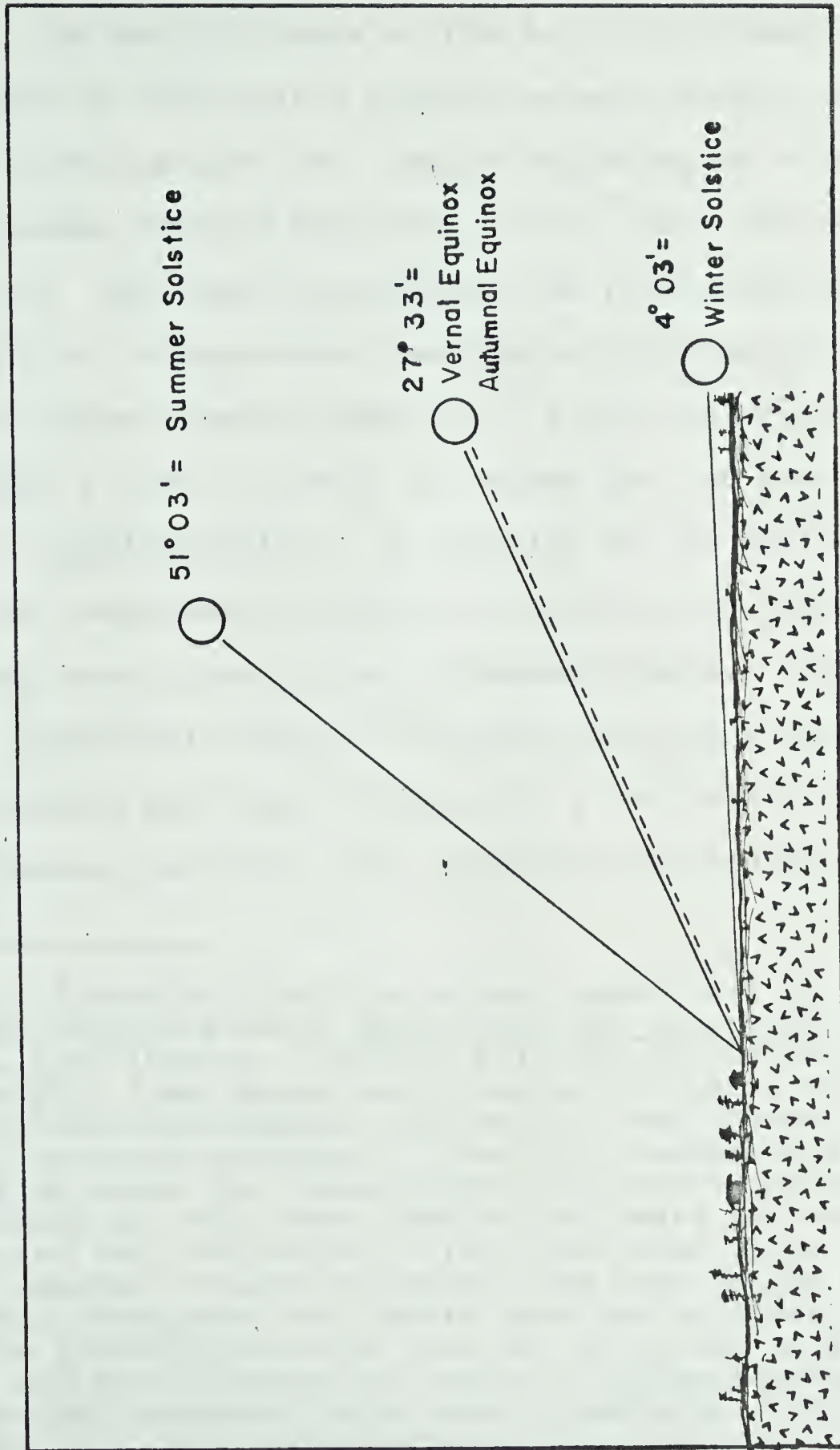


Figure 2-1

the solar rays penetrate most directly through the atmospheric shield, whereas in winter just the reverse is true.

The monthly means of the mean daily temperatures measured at Yellowknife Airport meteorological station during the twenty-five year period beginning in October, 1942, and running through September, 1967,² are presented in Figure 2-2. The graph illustrates the fluctuation of mean monthly air temperatures realized at Yellowknife (i.e., the annual range extends from -18.9° F. in January to 60.9° F. in July; a range of 79.8° F. exists for the year).

Continentality. In addition to the latitudinal control of temperature there are other factors that influence thermal conditions in the Yellowknife Area. The most important additional factor is the situation with respect to major land masses and water bodies, i.e., Yellowknife's extreme continental position. The physical relationships that cause

²Compiled from the Canada, Department of Transport, Meteorological Branch, Monthly Record Jan. 1943 through Sept. 1967 (Ottawa: Queen's Printer and Controller of Stationery). Even though data publication began in July, 1942, for Yellowknife Airport, the months from October to December, 1942, were not published; therefore, temperature and precipitation means for these months were approximated by using the means for the other twenty-four years and substituting them for the 1942 voids. Also, the water year, which extends from October through September, has been relied on more heavily throughout the thesis than the calendar year because: 1) the annual hydrologic data are presented on the water year base and are difficult to convert, 2) the meteorological data are mainly presented on a monthly basis and thus easily adjusted to a water year base, and 3) there are twenty-five years of hydrologic and meteorologic data for the Yellowknife Area presently available using the water year base and only twenty-four years using the calendar year.

Mean Monthly Temperature and Precipitation,
Yellowknife Airport



Mean Annual: Temp. = 21.9°F, Ppt. = 9.7 inches

Figure 2-2

large land surfaces to be considerably more extreme in seasonal temperatures than coastal or marine locations are well known.³

Yellowknife's situation of being at least 750 miles from the Pacific Ocean at the coast of the Alaskan Panhandle, 350 miles south of Coronation Gulf (a portion of the Arctic Ocean), and at least 650 miles west of Hudson Bay indicates its continental interior location. These great distances from major water bodies are one approximation of the continentality of the region, but other factors tend to accentuate these distances.

One of these factors is that the Arctic Ocean and Hudson Bay are frozen for a long winter season, and as such, they effect an extension of continental conditions. Great Slave Lake exhibits similar characteristics. T. A. Blair and R. C. Fite summarized this situation by stating:

For all these reasons, water areas heat slowly, store much energy, and cool slowly. They are great storehouses of heat. Large land areas have great and rapid temperature changes and little storage capacity. The oceans are conservative; the continents, radical. . . . It should be noted, however, that an ice-covered body of water acts much as a snow-covered land surface. It reflects a high percentage of the incident radiation; it warms

³ For example, see: G. T. Trewartha, An Introduction to Climate (4th ed.; New York: McGraw-Hill Book Company, 1968), pp. 27-29; A. N. Strahler, Introduction to Physical Geography (New York: John Wiley and Sons, Inc., 1965), pp. 45-46; or G. T. Trewartha, A. H. Robinson, and E. H. Hammond, Physical Elements of Geography (5th ed.; New York: McGraw-Hill Book Company, 1967), pp. 56-57.

little by day and cools rapidly by radiation at night.⁴

Another factor that accentuates the continentality of Yellowknife's temperatures is the Rocky Mountain barrier to the flow of air masses with marine characteristics from the North Pacific. The mountain barrier impedes the easterly flow of maritime air. If the Pacific air is able to cross the barrier, it is radically altered with respect to temperature and moisture content, and thus loses much of its marine character.

One factor that slightly counteracts the continental temperature regime at Yellowknife (especially summer temperatures) is its proximity to Great Slave Lake. Because of the slower heating rate of the Lake in summer and its slower cooling rate in early winter before the ice cover forms, the land areas adjacent to the Lake have slightly moderated temperature ranges in comparison to more removed locations. This effect of reducing the continentality of locations near large interior lakes has been discussed and mapped for the Great Lakes by R. J. Kopec.⁵

O. V. Johansson⁶ has presented a quantitative means

⁴T. A. Blair and R. C. Fite, Weather Elements, a text in elementary meteorology (5th ed.; Englewood Cliffs, N. J.: Prentice-Hall, Inc., 1965), p. 74.

⁵R. J. Kopec, "Continentality Around the Great Lakes," Bulletin of the American Meteorological Society, Vol. 46, No. 2 (February, 1965), pp. 54-57.

⁶O. V. Johansson, "Die Hauptcharakteristika des jährlichen Temperaturgauges," Gerl. Beitr. Geophysik., vol.

of describing the degree of continental versus maritime influence on a temperature regime. It is empirical, but allows a relative comparison of stations. His formula is

$$K = \frac{0.9 A}{\sin \text{Lat.}} - 14, \quad (2.1)$$

where: K = index of continentality;
 A = annual temperature range in °F.;
 Lat. = geographical latitude.

The constants were developed by using two extreme cases (i.e., Verkhoyansk, Siberia, and Thorshavn, Faro Islands), and assigning a value of zero to the extreme oceanic case and a value of 100 to the extreme continental station. In applying the formula to Yellowknife the following index of continentality is derived:⁷

$$K = \frac{(0.9) (79.8)}{.88661} - 14$$

$$K = 67$$

33, 1931, pages 406-428. Translated reference: F. A. Berry, E. Bollay, and N. R. Beers, Handbook of Meteorology (New York: McGraw Hill Book Company, Inc., 1945), p. 947.

⁷For purposes of comparison, the index of continentality was calculated for several additional North American locations and they are listed below:

NORTH AMERICAN INDICES OF CONTINENTALITY

Location	Index (K)
Alert, N.W.T.	= 46
Resolute, N.W.T.	= 51
Yellowknife, N.W.T.	= 67
Winnipeg, Manitoba	= 66
Edmonton, Alberta	= 49
Vancouver, B.C.	= 16
San Francisco, Calif.	= 2

Other Temperature Controls. Some of the other climatic controls of temperature deserve brief mention. The altitude of the Yellowknife Area is relatively low (the community is approximately 600 feet above sea level) which tends to reduce the diurnal range of temperatures especially in summer when, for example, compared to the moderate altitudes of southern Alberta.

As a result of the regional thermal properties, the Yellowknife Area is dominated by a semipermanent high pressure system during the long, cold winter season. This is replaced by low pressure systems in summer which tend to develop because of the rapid heating during the short summer. The cyclonic storm tracks lie well to the south of Yellowknife in winter, and in summer, cyclonic storms occur in the Area less frequently than in more southerly locations. Thus the sequential temperature fluctuations associated with the passage of cyclones are not as prominent in Yellowknife as they are at many mid-latitude locations.

Because of the inland situation, ocean currents are only important for their absence. Mountain barriers to the west of Yellowknife tend to accentuate the distance factor with regard to the warm Alaskan Current and the circulation of the Arctic Ocean has little influence on Yellowknife's temperatures.

Relation to Water Balance: The effect of temperature on the components of the water balance is considerable. The

great range of temperatures at Yellowknife produces long, extremely cold, winters and short, warm summers. For most of the year, water is greatly restricted in its movement. In fact, because of the constancy of the below freezing temperatures in winter, the precipitation received during the seven winter months⁸ tends to accumulate on top of the ground in the form of a snow cover.

During the five months when average mean monthly temperatures are above freezing, there is considerable heat received in the Yellowknife Area. This not only converts the total winter precipitation into a mobile medium, but also produces enough heat that plants and open water surfaces transmit moderate quantities of water vapor into the air. Evaporation and transpiration will be discussed in more detail in chapter IV, along with other components of the water balance at Yellowknife.

Precipitation

In a water balance evaluation, the amount of precipitation received provides the input to the system. It is the initial quantity that is potentially available for the various forms of output (or kinetic expenditures) of water, such as evaporation, transpiration, runoff, or the increase in stored water in the basin.

⁸ Average mean monthly temperatures from October through April are below freezing at Yellowknife Airport and in this paper are considered "winter" months.

This initial supply of precipitation in the Yellowknife Area is extremely small on a monthly basis throughout the year; therefore, the mean annual precipitation is quite limited too. At the bottom of Figure 2-2 is a histogram of the twenty-five year means of the monthly precipitations. The mean annual precipitation totals only 9.73 inches.

The individual precipitation events are also marked by the paucity of yield. Rain or snow is recorded more frequently than at some low latitude, dry climatic stations which receive the same annual total. However, the vast majority of precipitating hours are classed as "light" with almost no "moderate" or "heavy" occurrences.⁹

There are three main reasons for the small mean annual precipitation occurring at Yellowknife. One is that for most of the year, air temperatures are very low and, of course, colder air cannot hold as much water vapor as warm air. Therefore, especially during the winter, there is very little moisture in the air.

Secondly, there are few precipitation mechanisms occurring in the area. There is no significant orographic barrier that would stimulate local precipitation. Convection and cyclonic mechanisms very rarely occur in winter;

⁹For example, see: Canada, Department of Transport, Meteorological Branch, General Summaries of Hourly Weather Observations in Canada 1961, Ontario, Quebec, At. Prov., N.W.T. and Newfoundland (Ottawa: Queen's Printer and Controller of Stationery, 1962), p. 405.

in summer their infrequent occurrence is characterized by poor development.¹⁰

The third reason for Yellowknife's limited precipitation is that it is isolated from any major source of marine air. The Rocky Mountain complex is an effective barrier to any direct flow of maritime air into the Yellowknife Area from the warm North Pacific. Therefore, Yellowknife is situated in a rain shadow location with regard to any westerly flow of air from the Pacific. However, Pacific air masses are still the major source of moisture, but cyclonic and more limited convectional uplift of this air must exceed the levels reached during the mountain passage. Resulting precipitation is moderate in frequency and intensity.

Other water bodies do not supply much precipitation to the Yellowknife Area because of their distance, cool temperatures, limited size, lack of appropriate wind conveyance, or ice covered surfaces. Although the Rocky Mountains impede the flow of air from the west, the meridional air movement in the lee of the barrier is not greatly restricted. Airflow in a north-south path along the eastern slopes of the Rockies, however, does not yield very much precipitation.

¹⁰ Considering another storm type which is often associated with a well developed cyclone (i.e., the tornado), H. J. Critchfield cites Yellowknife as a remarkable exception because one did occur within the Yellowknife Area. He wrote, "Tornadoes are comparatively rare in the rest of the world [outside the contiguous United States]. One was sighted at Yellowknife, N.W.T., Canada, (Lat. 62° 28' N.), on June 19, 1962." See: H. J. Critchfield, General Climatology (2nd ed., Englewood Cliffs, N. J.: Prentice-Hall, Inc., 1966), p. 128.

The southward movement of air over the Yellowknife Area in summer is moving from the Arctic Ocean into an area of higher temperatures. Although this tends to cause instability in the lower layers, the polar continental air contains a small quantity of water vapor and, with warming, its capacity to hold moisture increases. The northward flow of air into the Yellowknife Area is down the slope of the Mackenzie valley. These air masses have lost much of their moisture previously during the long passage over land areas to the south.

The annual regime of precipitation indicates a moderate concentration in the summer and early autumn. (See Figure 2-2.) This is related to the increased frequency of precipitating mechanisms, plus the increased water vapor holding capacity of the warmer air prevailing during this period. Conversely, the higher air temperatures correspond to increased demands for moisture by plants and increased rates of evaporation from free water surfaces.

The very small monthly precipitation totals which are prevalent during the cold season are, in essence, compounded on the surface to form the snow cover. The winter snow that accumulates and is detained on the surface, is finally reactivated en masse with the thawing spring temperatures. This conversion of accumulated winter precipitation to an effective spring supply of liquid moisture yields anomalously wet conditions for a short time.

All of these precipitation characteristics have relevance to the water balance of the Yellowknife Area.

Considerations of the snow aspects of precipitation are treated in chapter III and specific quantitative references are made to Yellowknife's annual precipitation in chapter IV.

Other Climatic Elements

Sunshine. The duration of sunshine is actually a measure of the amount of unobscured solar radiation received at a site. Direct sunshine is a major factor contributing to the heating of the earth's surface and, of course, the primary source of atmospheric heating is the earth's surface. Therefore, air temperature measurements are partly a measure of sunshine, but not as a distinguishable element.

H. Lippmann and H. E. Landsberg¹¹ have presented some interesting maps of estimated world distribution of sunshine. From these, Yellowknife's mean total sunshine for January is interpolated to be fifty hours, or less than two hours of sunshine per day. For July, the mean total equals 320 hours, or slightly more than ten hours per day. The mean total for the year is 1800 hours, which is approximately five hours per day throughout the year.¹²

¹¹H. Lippmann, "Mean January Sunshine (Hours), Map 1", and "Mean July Sunshine (Hours), Map 2," and H. E. Landsberg, "Total Hours of Sunshine (Annual), Map 3," World Maps of Climatology (2nd ed.; New York: Springer-Verlag New York Inc., 1965), maps in rear pocket.

¹²The maps are based on meteorological station observations of cloudiness using the formula:

$$S = T (10 - C) , \quad (2.2)$$

where: S = estimated monthly sunshine duration;

T = maximum possible monthly sunshine duration;

C = monthly mean cloudiness, in tenths.

Long-term records were used in compiling the maps, but the

Winds. The wind direction, velocity, and duration are important atmospheric phenomena that influence the water balance. The rate of evaporation and transpiration, and the direction and amount of drifting snow are related to the movement of the surface air layer.

The twelve monthly and one annual wind roses of Figure 2-3 illustrate mean wind values as recorded at the Yellowknife Airport during the ten year period of 1957 through 1966.¹³ The direction of the wind is indicated by the orientation of the line on the rose. The hourly duration of wind for any one direction is multiplied by the mean speed of the wind blowing from that direction. This yields a duration-intensity value for the wind in miles blown per hour for each direction. The lengths of the wind rose lines are in proportion to these values.

The general pattern of wind direction-duration-intensity indicates that the dominant direction is from the east in the winter with secondary flow coming from the northeast and the northwest. In summer the pattern is more variable with some prevalence from southerly directions.

authors felt that the formula yielded values that were "usually somewhat too low." See: Lippmann, "Mean January Sunshine (Hours), Map 1," map in rear pocket; and H. E. Landsberg, "Global Distribution of Solar and Sky Radiation," World Maps of Climatology (2nd ed.; New York: Springer-Verlag New York Inc., 1965), p. 2.

¹³ Canada, Department of Transport, Meteorological Branch, Climatology Division, Hourly Data Summaries - No. 78, Yellowknife Airport (Toronto: Department of Transport, 1968), pp. 6-8.

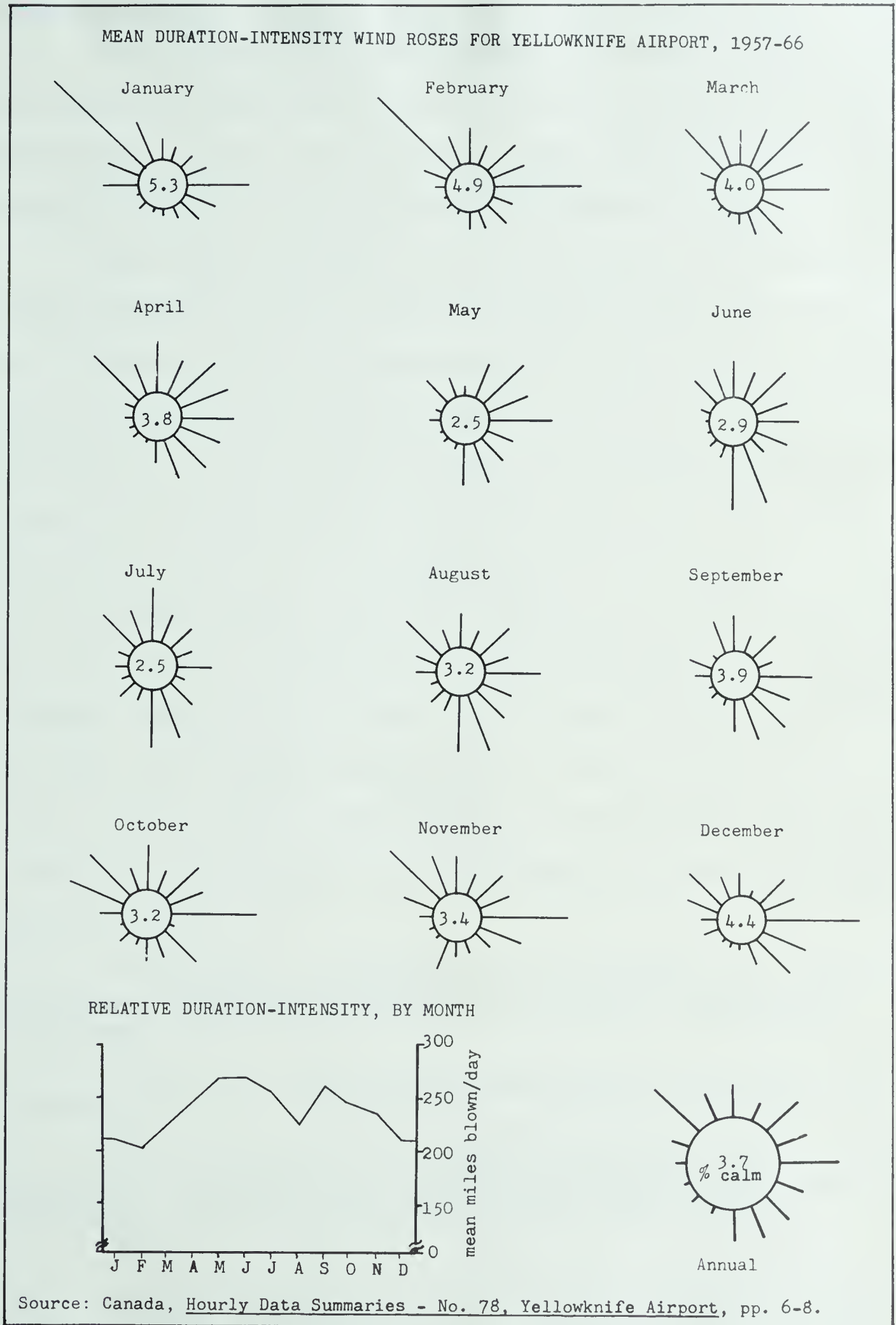


Figure 2-3

Classification

The climate of the Yellowknife Area can be summarized by considering the description of the class into which the Yellowknife Airport meteorological data fall according to various schemes of classifying world climates.

The modified Köppen climatic classification has been widely used in, and for, North America by such geographers as G. T. Trewartha,¹⁴ A. N. Strahler,¹⁵ H. M. Kendall, R. M. Glendinning, and C. H. MacFadden,¹⁶ plus many others. According to this classification, the Yellowknife Area is centrally located in the "Subarctic" climatic class. The Subarctic climate is characterized by an "average temperature of the warmest month over 50° F. and of the coldest month 32° F. and below."¹⁷ The classification specifies also that the "average temperature of from one to three months [is] 50° F. or above, and average temperature of warmest month [is] below 71.6° F."¹⁸ Kendall, Glendinning, and MacFadden stated further that there cannot be a significant seasonal concentration

¹⁴Trewartha, An Introduction to Climate, pp. 237-391, and also, Trewartha, Robinson, and Hammond, Elements of Geography, pp. 128-201.

¹⁵Strahler, Introduction to Physical Geography, pp. 102-165.

¹⁶H. M. Kendall, R. M. Glendinning, and C. H. MacFadden, Introduction to Physical Geography (New York: Harcourt, Brace and World, Inc., 1967), pp. 243-286.

¹⁷Ibid., p. 357.

¹⁸Ibid., p. 360.

of the precipitation, and that the Subarctic class is a moist climate with no distinct season of moisture deficiency.

Strahler summarized the Subarctic climate by saying that:

This climate lies in [the] source region of continental polar (cP) air masses, which in winter are stable and very cold. Summers are short and cool. Annual temperature range is enormous. Cyclonic storms, into which maritime polar (mP) air is drawn, supply light precipitation, but evaporation is small and the climate is therefore effectively moist.¹⁹

The Atlas of Canada²⁰ adopted a more direct version of Köppen's classification; however, the only major difference is that the maximum temperature limit for the coldest month is 26.6° F. rather than the 32° F. modification. C. Troll has mapped the world's climatic characteristics according to his classification system which he terms "The Seasonal Climates of the Earth,"²¹ but for northern regions at least, it does not appear to vary much from Köppen's divisions. Under Troll's classification, Yellowknife is centrally located in category II3 termed "Cold-temperate Boreal Zone-highly continental boreal climate." The class description states that it has an:

(annual fluctuation greater than 40° C) with permanently frozen soils, very long, extremely cold and

¹⁹ Strahler, Introduction to Physical Geography, p. 111.

²⁰ Canada, Department of Mines and Technical Surveys, Geographical Branch, Atlas of Canada (Ottawa: Queen's Printer and Controller of Stationery, 1958), plate 30.

²¹ C. Troll and K. H. Paffen, "Seasonal Climates of the Earth, Map 5," World Maps of Climatology (2nd ed.; New York: Springer-Verlag New York Inc., 1965), map in rear pocket.

dry winters (coldest month below -25° C) short, but sufficient warming up in summertime (warmest month $+10^{\circ}$ to $+20^{\circ}$ C) and deep thawing soils: highly continental dry coniferous woods.²²

Recently, D. B. Carter compared the Köppen climatic classification to that of the "improved," "extended," and "regularized" system developed by Thornthwaite. Carter concluded that:

In terms of its internal logic and the precision of its criteria, the Köppen system has been superseded by that of Thornthwaite. Preference for the older classification which has been almost unanimous among geographers cannot be supported on grounds of its intellectual adequacy. The Köppen system has degenerated into a dogma.²³

Therefore, consideration of Yellowknife's general climate should include the applicable Thornthwaite class description. M. Sanderson applied the Thornthwaite classification to all of Canada.²⁴ The Yellowknife Area was located centrally in the "microthermal, dry subhumid" class. More descriptively, this means that Yellowknife has a moderately large deficit compared to an existent, but small, annual

²²C. Troll, "Seasonal Climates of the Earth, the seasonal course of natural phenomena in the different climatic zones of the earth," World Maps of Climatology (New York: Springer-Verlag New York Inc., 1965), p. 26.

²³D. B. Carter, "Farewell to the Köppen Classification of Climate" in "Abstracts of Papers Presented at the 63rd Annual Meeting of the Association of American Geographers, St. Louis, Missouri, April 11-14, 1967," Annals of the Association of American Geographers, Vol. 57, No. 4 (December, 1967), p. 784.

²⁴M. Sanderson, "The Climate of Canada According to the New Thornthwaite Classification," Scientific Agriculture, Vol. 28, No. 11 (November, 1948), pp. 502 & 515.

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TO THE EDITOR OF THE JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

FROM THE DEPARTMENT OF CHEMISTRY, UNIVERSITY OF CHICAGO

RE: [Illegible Title]

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surplus. With regard to the thermal efficiency index which was applied to Yellowknife, the microthermal designation indicates that the potential evapotranspiration, estimated from mean monthly temperature and a length of day factor, is "low" annually (i.e., between 11.22 and 16.83 inches).²⁵

Basic to Thornthwaite's climatic classification is his use of the water balance concept in determining pertinent climatic factors. Since detailed investigation of some of the water balance components at Yellowknife comprises the core of this thesis, further detail about Thornthwaite's approach will be presented in subsequent chapters. It is sufficient here to say that Yellowknife's climate can be described as having a severely cold winter and a short, warm summer with some indication of moisture deficiencies in late summer.

Terrain

With regard to general terrain, "Canada is naturally divided into five main regions each possessing characteristic geological features and, as a result, more or less distinctive physical features."²⁶ The Yellowknife Area lies entirely within the extensive Precambrian Shield physiographic

²⁵C. W. Thornthwaite, "An Approach Toward A Rational Classification of Climate," Geographical Review, Vol. 38, No. 1 (January, 1948), pp. 75-85.

²⁶C. H. Stockwell, ed., Geology and Economic Minerals of Canada, Geological Survey of Canada, Economic Geology Series No. 1 (Ottawa: Queen's Printer and Controller of Stationery, 1963), p. 1.

region. Geologically, the Shield is very complex in structure and rock types. The complexity and the lack of fossils from the Precambrian Era have impeded detailed geological interpretation of the Shield. However, it is known that these ancient rocks have undergone several orogenic periods which resulted in considerable folding and faulting accompanied by lava flows and igneous intrusions.

Deformation in the Yellowknife Area is exemplified by the fact that "originally flat lying rocks have been tilted to near vertical positions, or else contorted into tight folds of varying altitudes. The major structure is thought to be a syncline, the axis of which plunges north up the center of Yellowknife Bay,"²⁷ Faulting in the Yellowknife Area Shield is prominent. The trend of the faults is north and northwest with some large cumulative horizontal and vertical displacements. The West Bay fault, which runs along the west shore of Yellowknife Bay, is the largest break and has been traced for more than 150 miles. The gold (and other metallic mineral) ores that have been mined in the Area are found in these shear zones and associated country rock.

The Yellowknife Area was completely covered by glaciers during the Wisconsin time. This is evident from the numerous glacial erosional and depositional landforms present.

²⁷ "The Yellowknife Operations of Giant Yellowknife Mines Limited" (unpublished dittoed paper distributed by Giant Yellowknife Mines Limited, Yellowknife, N. W. T.), p. 3.

These landforms, plus minor glacial features such as striations, crescentic gouges, and crescentic fractures indicate a general ice movement from the east-northeast. (See Figures 2-4 and 2-5.) On the basis of stratigraphic relationships and radiocarbon dates, it has been suggested by B. G. Craig that the area just east of the Yellowknife Area was deglaciated about 7,000 years before the present time.²⁸

The glacially eroded Shield bedrock remains as rounded hills and scoured basins, plus numerous roche moutonnées. Such depositional features as glacial lacustrine deposits, thin ground moraine deposits, and erratics are characteristic of the Area.²⁹ Since deglaciation, the surficial deposits have been weathered and eroded slightly by subaerial processes. The results are exposed bedrock knolls and partially filled basins containing mineral and organic deposits. The drainage is still distinctly deranged from the glacial action and there is a large proportion of surface area covered by lakes. Also, many of the poorly drained depressions contain bogs and muskegs.

This type of glacial topography has distinct

²⁸ B. G. Craig, Surficial Geology of East-Central District of Mackenzie, Geological Survey of Canada, Bulletin 99 (Ottawa: Queen's Printer and Controller of Stationery, 1964), p. 39.

²⁹ B. G. Craig, Glacial Lake McConnell, and the Surficial Geology of Parts of Slave River and Redstone River Map-Areas, District of Mackenzie, Geological Survey of Canada, Bulletin 122 (Ottawa: Queen's Printer and Controller of Stationery, 1965), p. 14.

Figure 2-4. Crescentic gouges and crescentic fractures in fine grained quartz near head of Pocket Lake basin. Pencil pointing west-southwest and indicating direction of ice movement.

Figure 2-5. Glacial grooving on stoss side of roche moutonnée in old Yellowknife town site. View looking northwest and glacial movement was from right to left in photograph.

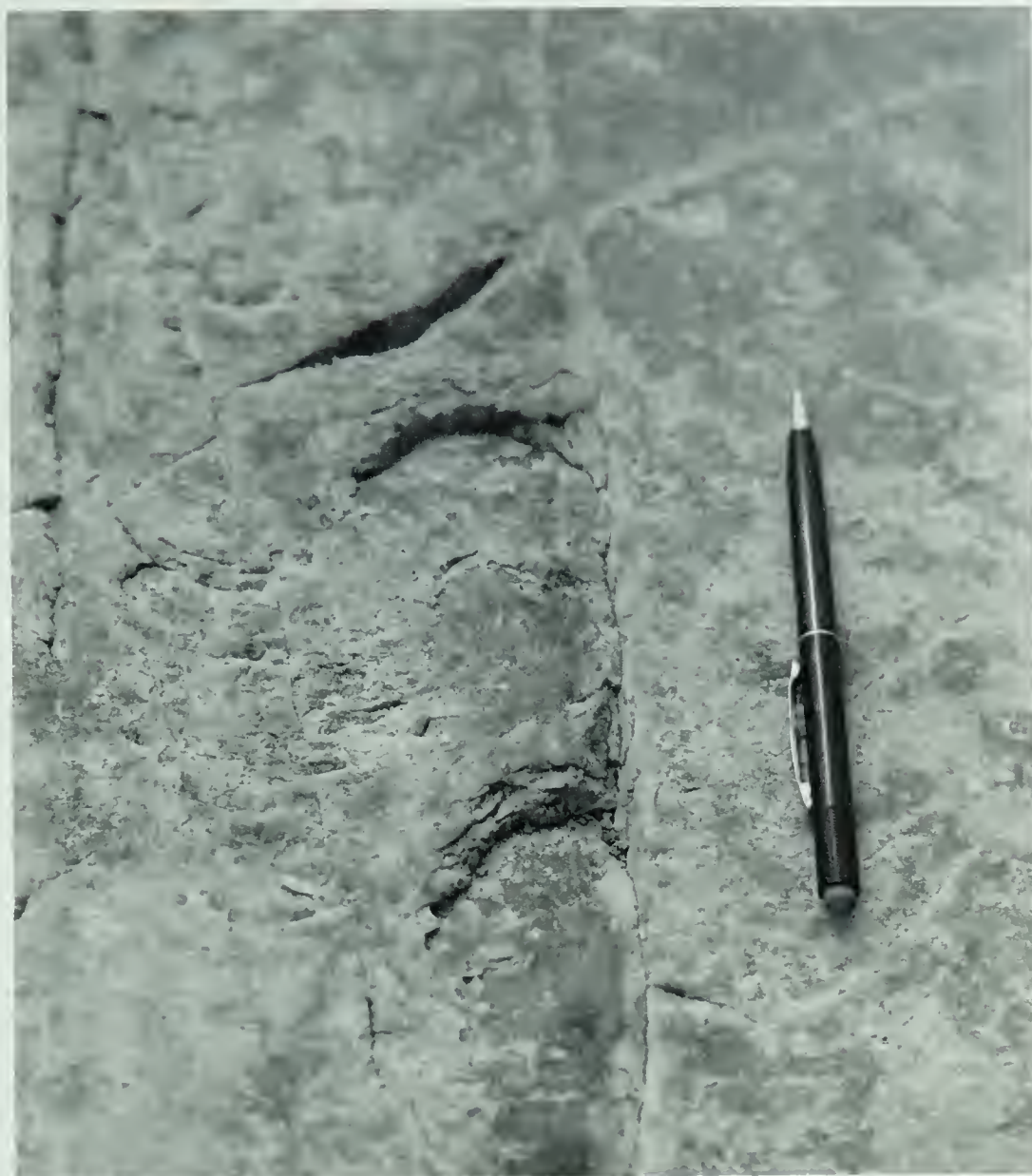


Figure 2-4



Figure 2-5

influences on water balance conditions, such as the form of water drainage from the land, infiltration rates, and the length of the delay between surplus precipitation and stream discharge.

Soils

Variations in types of soils are caused by different combinations of climate, vegetation, parent material, slope and drainage, and time. In the Yellowknife Area, the two most important factors of zonal soil development (i.e., climate and vegetation) are such that podzolic soils would be expected. These podzols are characterized by: 1) slowly decaying organic material in the A_0 layer of the A horizon, 2) a colloid rich, humus rich, dark gray A_1 layer, 3) a light gray, leached and eluviated A_2 layer, and 4) a brownish B horizon of illuviation.

In this cold climate, soil development is not rapid. The restriction of soil moisture drainage by seasonal or perennial ice conditions, the resistant bedrock, and poor regional drainage from scour basins are contributing factors to the slow rate of soil formation. Also important to the limited soil development in the Yellowknife Area is the fact that glaciation removed all previously existing soil.

The time period since deglaciation has not been sufficient for the extensive development of zonal soil under the podzolization process. Therefore, there is a predominance of azonal and intrazonal soils in the Yellowknife Area instead

of zonal podzols. In fact, rather than according to zonal characteristics, the soils of the Area can be more accurately classified as: 1) bare bedrock, 2) stony glacial till and weathered bedrock, 3) organic, and 4) bog and muskeg soils. Of course, the Area is currently influenced by the podzolization process and so the intrazonal and azonal soils are being slowly modified by this developmental process.

The duration of snow cover in the Yellowknife Area produces some interesting relationships with regard to soil and surficial conditions. Very high albedo and low conductivity are thermal properties; B. T. Bunting has presented some other properties:

Snow influences soils, acting as a store of moisture and, if thawing slowly, moistens the upper layers. Rapid thaw causes erosion on steep slopes and on bare fields. Some Russian writers regard snow as a semipermanent soil horizon; it can be ploughed or compacted to prevent rapid thaw, and it supplies not only moisture, but 1 ton/ha of nutrients and 9 tons/ha of organo-mineral particles to the soil.³⁰

Soils in general, have significant influences on factors of the water balance in that they influence infiltration rates, water retention quantities, and plant-moisture relations.

Permafrost

Although some confusion has arisen about the definition

³⁰ B. T. Bunting, The Geography of Soil (Chicago: Aldine Publishing Company, 1965), p. 65.

of permafrost,³¹ the following statement by R. J. E. Brown of the Canadian National Research Council will suffice for this thesis:

Permafrost is defined as the thermal condition under which earth materials exist at temperatures below 32° F. continuously for a number of years. Thus, all earth materials including bedrock, gravel, sand, silt, clay, peat, or mixtures of these materials may exist in a perennially below 32° F. condition. Permafrost is defined exclusively on the basis of temperature irrespective of texture, degree of induration, water content, or lithologic character.³²

A recent map by Brown portrays the current knowledge of the distribution of permafrost in Canada.³³ On this map, the Yellowknife Area falls within the discontinuous permafrost zone, but with the indication that "widespread permafrost" occurs. A specific observation for Yellowknife was noted on the map and reported a permafrost thickness of 200 to 300 feet.

Permafrost influences water balance relationships significantly. When ground temperatures are perennially below freezing, water will be mostly in the ice phase, and thus is not a mobile, interacting water balance factor. Additions of water through infiltration or percolation will tend to freeze, and thus be removed from the mobile water balance. Also, the

³¹P. J. Kakela, "Problems in Defining Permafrost," The Albertan Geographer, No. 1 (April, 1965), pp. 5-10.

³²R. J. E. Brown, personal letter dated February 2, 1965.

³³R. J. E. Brown, Permafrost in Canada, Geological Survey of Canada in cooperation with the National Research Council of Canada, Map 1246 A (Ottawa: Department of Energy, Mines and Resources, Surveys and Mapping Branch, 1967).

formation of new ice can disrupt the soil structure³⁴ and impede plant root development. An impervious permafrost layer will prevent the percolation of moisture and lead to distinct subsurface drainage characteristics.

The active layer above the permafrost table is also important to the water balance. Here, stored moisture in the ice phase is slowly released to the dynamic water balance through the summer months which influences soil moisture and stream discharge regimes. The freeze-thaw process in the active layer has distinct effects upon surficial materials in both a weathering (congelifraction) and erosional (congeli-turbation) nature.

Some vegetational types that survive freezing air temperatures can be killed in the root zone by ice formation. "Winter wheat, for example, can withstand freezing temperatures but is winter-killed if the roots are disturbed too much by frost-heave."³⁵ Certainly, the permafrost table imposes a limit to the depth of plant rooting. Plant cover, in turn, can influence the thickness of the active layer. The "drunken forest"³⁶ effect is one result of the interaction

³⁴P. J. Kakela, "Some Aspects of the Origin and Distribution of Permafrost" (unpublished Ph.D. Candidacy Public Lecture and Paper, Department of Geography, University of Alberta, February 24, 1967), p. 15.

³⁵Critchfield, General Climatology, p. 270.

³⁶G. H. T. Kimble and D. Good, editors, Geography of the Northlands (New York: John Wiley and Sons with the American Geographical Society, 1955), p. 102.

between vegetative cover and the fluctuating permafrost table.

Vegetation

The Yellowknife Area lies within the "Subarctic Forest-Tundra Transition" vegetation belt.³⁷ This means that the Yellowknife Area is on the forested side of the Arctic tree line, but the trees are stunted as a result of the harsh climate and there are open moss-lichen areas interspersed with the wooded areas. Of course, there are many bare bed-rock outcrops that only support a spotty covering of crusty lichens. (See Figure 2-6.)

The Area has a large proportion of hygrophytes associated with the poorly drained depressions. Such depressions frequently undergo a transition through time from open water (lake) to bog and eventually to muskeg conditions. The duration of cold temperatures hampers bacterial decay of organic matter and therefore, thick peat layers result. (See Figure 2-7.)

The vegetation of the Yellowknife Area can be grouped into five descriptive categories. They are: 1) stunted trees and bushes, 2) dry, moss covered basins, 3) muskegs, 4) bogs, and 5) lichen covered rock outcrops. Besides developing in response to certain water balance characteristics, these vegetational groups influence water conditions

³⁷ Canada, Department of Mines and Technical Surveys, Geographical Branch, Atlas of Canada, plate 38.

Figure 2-6. Intermixing of stunted trees and moss-lichen vegetation. Looking south down West Bay Fault with Giant Yellowknife Mines Limited "B" shaft in center.

Figure 2-7. Thick organic layer collected in poorly drained depression in Pocket Lake basin. Pit revealed frozen ground at about six inches below surface of small mound (knife stuck in frozen ground). Taken May 20, 1967.



Figure 2-6



Figure 2-7

by, for example, tapping different depths of soil with their roots or influencing moisture retention.

Pocket Lake Basin

Pocket Lake basin is a 37.1 acre drainage basin located four miles north of the new Yellowknife town site and about a mile northwest of Giant Yellowknife Mine's "C" shaft. It is a part of the larger Baker Creek basin which has been selected by the Canadian National Committee of the International Hydrologic Decade to be investigated as one of the Decade research watersheds.³⁸ Pocket Lake basin has been selected for special research attention within the Baker Creek Project, and thus much of the field work presented in this thesis was carried out in this small basin. Some of the advantages of working within a small drainage basin are that:

The research watershed provides an opportunity for the examination within a limited region of hydrologic processes on a quantitative basis. Limitation of research watersheds to sizes in the 10 acres to 25 square miles range provides for a degree of homogeneity of climatic, physiographic, geologic and land use factors not attained on river basins regularly gauged.

The objectives of research watershed programs are of two types: 1) to gain a better understanding of the natural hydrologic processes, 2) to provide quantitative data for application in land and water management practices within particular geographic regions.³⁹

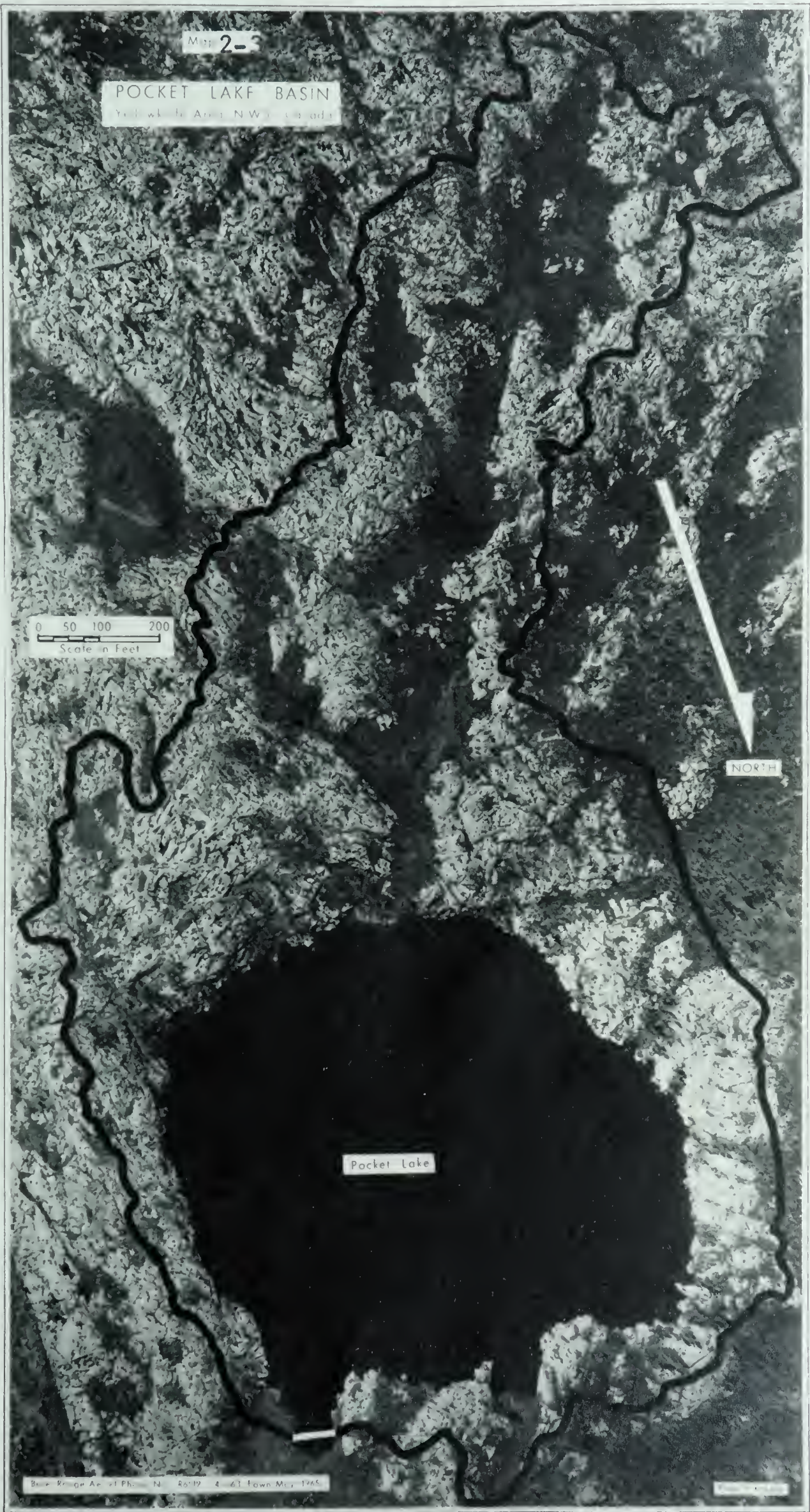
³⁸"The International Hydrologic Decade Baker Creek Basin Project" is supported by a National Research Council of Canada grant and directed by A. H. Laycock, Department of Geography, University of Alberta, Edmonton, Alberta.

³⁹F. R. Hore and H. D. Ayers, "Objectives of Research

Map 2-3 is an aerial photograph of Pocket Lake basin. Pocket Lake itself is circular in form with some very steep rock shores. It drains to the north towards Baker Creek. The major drainage channel leading into Pocket Lake is from the south and drains the greatest portion of muskeg in the basin. In fact, this channel way is stair-stepped in profile, dropping from the uppermost muskeg filled depression to the middle muskeg to the lower muskeg and finally descending abruptly into the Lake. Most of the rest of the basin is dominated by rounded bedrock knolls and small, dry, moss covered depressions. All drainage into Pocket Lake is ephemeral.

Map 2-4 is a contour map, with a two foot contour interval, of Pocket Lake basin. This map illustrates the relative relief and amount of slope within the basin. (Note that the datum plane for the map was established with regard to a reference level of Giant Yellowknife Mines, Limited, and not to mean sea level.)

Soil conditions in Pocket Lake basin differ from those of the Yellowknife Area mainly with regard to their areal proportionment. That is, there is probably slightly more area of bare bedrock (and open water surface), and slightly less bog and muskeg type soil conditions in Pocket Lake basin





Drawn by Range Aerial Survey Ltd., Oct. 1966
from May 1965 Air Photos

than is generally the proportion throughout the Yellowknife Area.

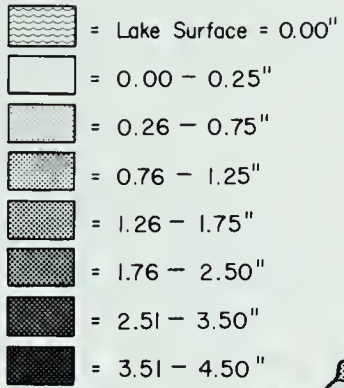
The terrain within Pocket Lake basin was analyzed on the basis of its capacity to hold water against the pull of gravity in spring. That is, the maximum quantities of water that would be available for evaporation and transpiration from different surfaces were evaluated and these quantities will be referred to as "surface retention capacities" subsequently in this thesis. The investigations involved field measurements and observations in addition to the examination of aerial photographs in and out of the field. For the bedrock surfaces, the amount of slope and roughness of the rock surfaces were observed during the wetting conditions of the spring thaw. Relative differences were first distinguished, and later, quantities were suggested for the surface retention capacities of the relative categories. In the well drained, coarse soil areas the texture and depth of rooting were evaluated in the field with regard to their water holding capacities. For the moss covered surfaces the depth to frozen ground was measured in numerous locations during the spring melt. This measurement and an evaluation of water held within the thawed soil and ponded above the soil as a result of the poor drainage from the bedrock depressions provided the evaluation of retention capacities for these surfaces.

From these investigations, categories of water retention during the spring snow melt season were established and mapped for Pocket Lake basin. Map 2-5 portrays the distribution of these categories. This map will be used in an analysis of water surplus relationships resulting from the spring snow cover of Pocket Lake basin as presented in Chapter III.

MAP 2-5

SURFACE RETENTION

POCKET LAKE BASIN
Yellowknife Area, N.W.T., Canada

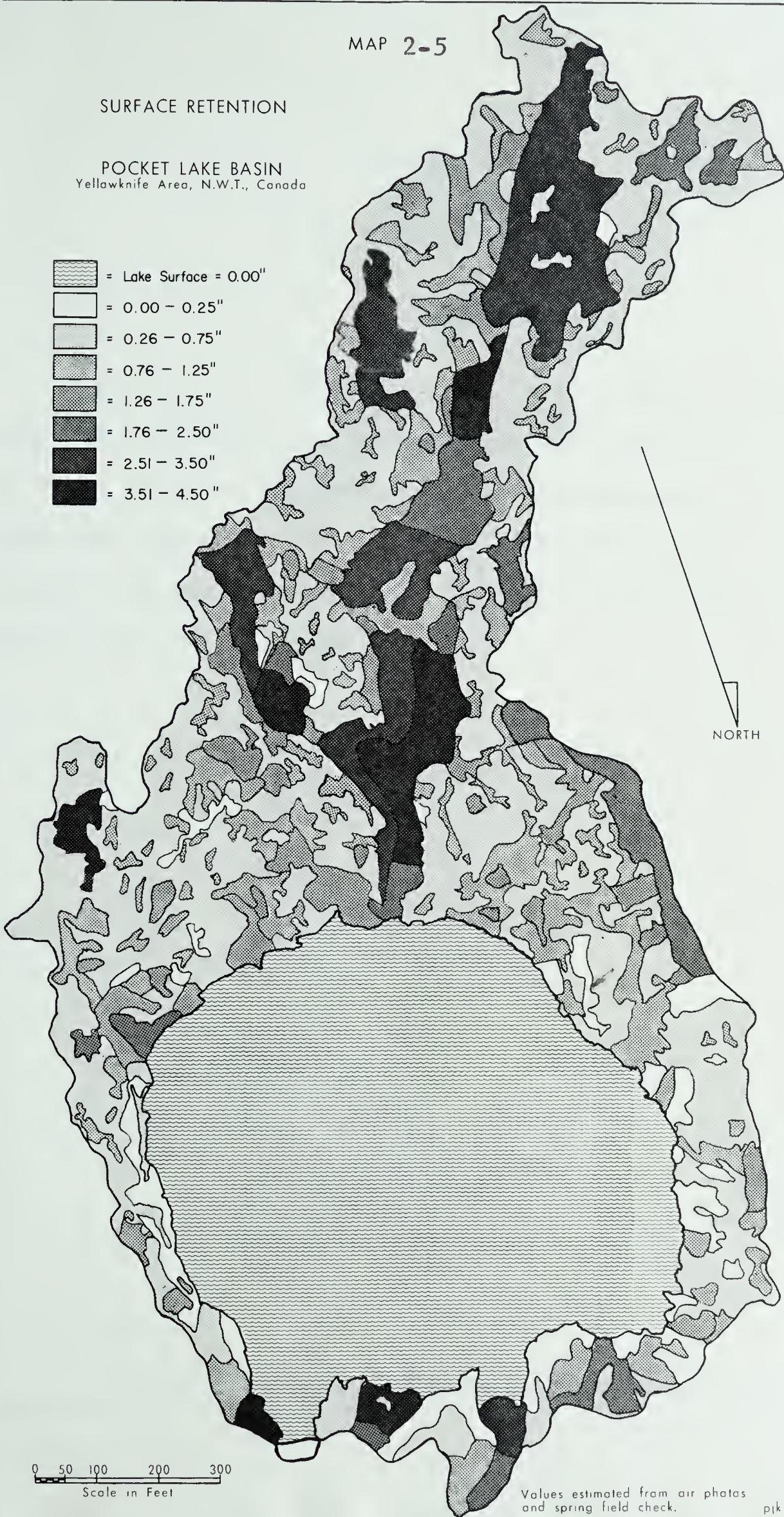


NORTH

0 50 100 200 300
Scale in Feet

Values estimated from air photos
and spring field check.

pik



CHAPTER III

SNOW PRECIPITATION

Introduction

Snow is a solid form of precipitation. It results from the sublimation of water vapor into small ice particles at below freezing temperatures in the atmosphere. The ice particles unite to form hexagonal crystals which, when heavy enough, are precipitated from the air. In a less prosaic style, Joan Swift wrote:

Snow

These stars do not bother
to be constellations.
Cassiopeia has tired
of her rigid chair,
Cygnus of wings
which cannot beat.
Skirts and feathers swirl
through the bare twigs
and around my head.
Who could have dreamed
the universe so unruly?
Best to remember
it's all in the point of view.
These galaxies,
if you should touch them,
would disappear,
though on your fingers
and in your hair
would glisten
the most crystalline
bells of water.¹

¹J. Swift, "Snow", The Reporter, Vol. 37, No. 8
(November 16, 1967), p. 46.

Snow precipitation is received at least once a year by a large portion of the earth's surface. With high altitude or high latitude, snow becomes more prominent. For the Yellowknife Area, snow covers the ground continuously for approximately one-half of the year, and contributes some 40 to 50 per cent (or more) of the water received annually.

The analysis of certain water balance components (e.g., runoff, precipitation, or soil moisture recharge) in the Subarctic is highly dependent on knowledge of snow. The snow cover influences other relevant environmental conditions too, such as: 1) the rate and depth of fall frost penetration and spring thawing of the ground, 2) the albedo of different ground surfaces, 3) the rate of freeze up and breakup of rivers and lakes, and 4) the amount of winter insulation provided to low growing plants and plant roots.

This chapter, therefore, presents the results of field work directed toward analyzing the spring snow cover and its melt on an areal basis for Pocket Lake basin. The collected field information is considered with an understanding of available snow observations made at the nearby Yellowknife Airport meteorological station. Aspects of the snow cover are mapped and a sequence of photographs taken from the air are used to illustrate stages of melt through the spring.

Point Measurements

The measurement of snow precipitation caught by a gauge or for a spot sample as it accumulated on the ground

has been observed and recorded at the Yellowknife Airport since 1942 as part of the Canadian Department of Transport, Meteorological Branch, observation program. In explaining the measurement of precipitation, the Meteorological Branch published this statement:

. . . snowfall is taken as the depth of freshly fallen snow (measured with a ruler) in an area free from drifting. Precipitation is taken to be the rainfall plus one tenth the snowfall. The unit in all cases is the inch. From November 1, 1960 onward the stations equipped with Nipher snow gauges [which included Yellowknife Airport] measured the water equivalent of the snow directly. At these stations precipitation is recorded as the rainfall plus the water equivalent of the snowfall. . . .²

There are several shortcomings to such point measurements of snowfall. First, the specific gravity of freshly fallen snow and the snowpack varies considerably from the .10 value that was used as the standard conversion factor until 1960. Secondly, it is often difficult to find a sampling site that is "free from drifting," and furthermore, for some studies (e.g., runoff), it is the amount of drifting that is really important. A third shortcoming involves the recent use of the Nipher gauge. Even though it circumvents the problem of density variations and drifting on the ground surface, it introduces the problem of gauge catch accuracy (which was mentioned in chapter I). The gauge is still a point measuring device and thus does not indicate the variations in snow

²Canada, Department of Transport, Meteorological Branch, Monthly Record, September 1967 (Ottawa: Queen's Printer and Controller of Stationery, 1968), p. 3.

accumulation that occur on different, local land surfaces. Even though point measurements are imperfect,³ they provide one of the few long period measures of a water balance factor in the Yellowknife Area.

In calculating the water balance according to the Thornthwaite procedure, it is important to know the form of precipitation, i.e., rain or snow. At the time of fall, rain takes a dynamic role in the water balance because of its liquid character, whereas, snow accumulates and is detained on top of the ground surface through the winter and does not actively enter into the water balance until the spring melt. On the basis of mean monthly temperatures, Thornthwaite and Mather wrote that "if the temperature is below -1°C . [30.2°F .] it is assumed that the precipitation falls as snow."^{4,5}

Using the mean monthly temperature and precipitation records published for Yellowknife Airport and also using

³ Adjustments to these recorded values will be presented in chapter IV with the analysis of the Yellowknife Area water balance.

⁴ C. W. Thornthwaite and J. R. Mather, "Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance," Publications in Climatology, Vol. X, No. 3 (Centerton, N. J.: Drexel Institute of Technology, Laboratory of Climatology, 1957), p. 191.

⁵ Thornthwaite and Mather conversely considered precipitation occurring at mean monthly temperatures above -1°C ., or 30.2°F ., to be rain, but failed to specify the form of the precipitation if the mean monthly temperature is exactly 30.2°F . The mean monthly temperature for October, 1952, was 30.2°F . and for the purposes of the monthly calculations of the water balance using the Thornthwaite procedure, the .70 of an inch of precipitation received in that month is considered to be rain.

Thornthwaite and Mather's temperature boundary, the writer has derived a mean snow accumulation of 4.36 inches per winter on the basis of the twenty-five years of record.⁶ The writer believes that for most years the Thornthwaite and Mather temperature boundary includes a portion of rain as "snow" and that only seldom is there any actual snowfall that is misinterpreted as "rain." Therefore, the estimated seasonal snow accumulation values are probably higher than the actual amount of snow cover.

The writer believes that this is caused by the character of temperature change and quantity of precipitation in the transitional fall and spring months. In fall, the early October temperatures at Yellowknife are usually above freezing and the precipitation that occurs is rain. The latter part of October is characterized by persistent freezing temperatures with snow precipitation. Usually the freezing temperatures are low enough and for a long enough portion of the month to produce a mean monthly temperature below 30.2° F. Thus, because of the rapid and severe temperature decrease in October, some rain would be classed as "snow" according to the Thornthwaite and Mather mean monthly temperature value. With rising temperatures in spring, the reverse situation could occur. That is, some snow received in early May would be

⁶Again the water year (i.e., October 1 through September 30) has been used for the 12 month base because, first, it allows comparison of meteorological data with streamflow data published on a water year basis, and secondly, it allows each winter snow accumulation period to be uninterrupted.

considered "rain" because the mean monthly temperature is usually above 30.2° F. However, this error would normally be smaller in quantity than the fall error because the mean monthly precipitation of May is smaller than October.

The 1966-67 water year can be used as an example to illustrate the overestimation of snow. Using the Thornthwaite and Mather temperature boundary, an estimated 4.56 inches of snow water equivalent would have been received. The mean monthly temperature for October, 1966, was 23.5° F. (i.e., well below the 30.2° F boundary) and the monthly total precipitation of 1.64 inches would form the initial snow cover of the season according to the estimates. Figure 3-1 is a graph of the daily maximum and minimum temperatures and daily precipitation for Yellowknife Airport through the water year 1966-67. It can be seen from the graph that October maximum daily temperatures descended from the mid-forties at the first of the month to near zero at the end of the month. Before the fifteenth of the month, maximum temperatures seldom failed to rise above freezing, but after the fifteenth they remained below freezing until the spring. Therefore, on a daily basis, the 1.16 inches of precipitation that fell on or before October 15, 1966, were apparently rain or snow that was quickly melted when temperatures rose above freezing. The .48 of an inch of precipitation that fell during the latter part of the month was apparently in the form of snow.

In spring, there was very little precipitation during the period when temperatures were climbing above zero, so that

Fig 3-1

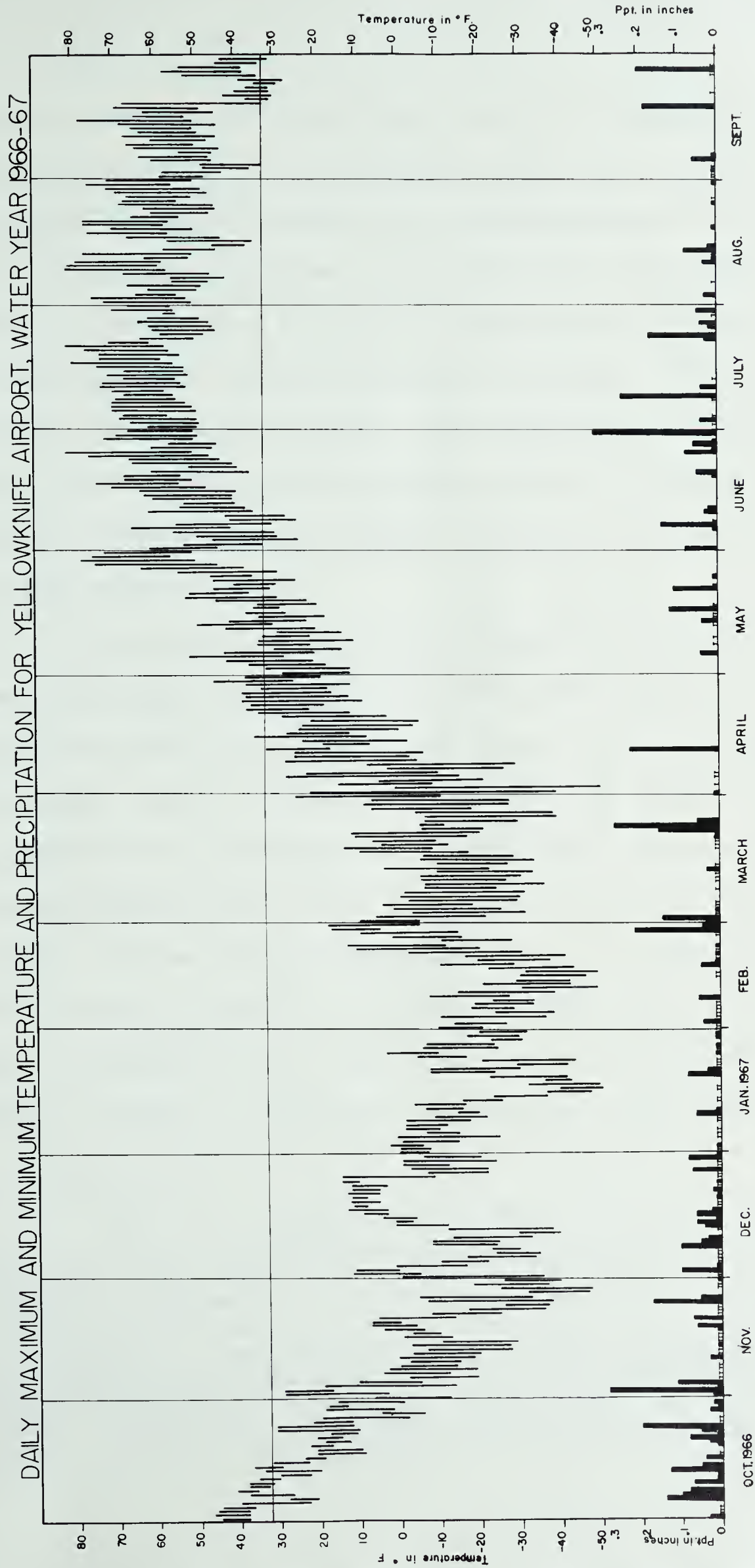


Figure 3-1

there is only an insignificant chance of erroneously estimating spring snowfall. Therefore, the total seasonal snowfall for 1966-67 would be reduced to approximately 3.50 inches. The writer also believes that the twenty-five year mean snowfall, as determined by the Thornthwaite and Mather temperature value, would be reduced slightly. Because 1966-67 had a wetter than average October, the adjustment to the long-term mean value would not be as great, and it is suggested that the twenty-five year mean snowfall is about 4.00 inches as measured at the point of fall.

The amount of snow that accumulates on the ground surface throughout the winter is even less than the total snowfall occurring after air temperatures are consistently below freezing. There are two factors that can cause this reduction in snow cover accumulation. First, the initial autumn snowfalls usually result from a cold air mass that moves into the region and the precipitated snow falls on a land surface that has not quite cooled to freezing. Thus, some of the early snow is melted by the land even when air temperatures remain below freezing. Secondly, sublimation⁷ from the snowpack

⁷See, for example: E. D. Sabo, "Evaporation from the Snow Cover in the Ergeni District;" P. F. Idzon, "Evaporation from the Snow Surface According to Observations at Dzhanybek;" and N. A. Mosienko, G. V. Pavlenko, and Yu. V. Khudomyasova, "Evaporation from the Surface of a Snow Cover Under Steppe Conditions of West Siberia" in Selected Articles on Snow and Snow Evaporation (Washington: U. S. Department of Commerce, Office of Technical Services, translated from Russian by Israel Program for Scientific Translations, 1963), pp. 14-21, 22-24, and 25-28 respectively.

could cause a loss of stored moisture while temperatures are below freezing. Because the quantities of snow sublimated are so small and difficult to measure, these losses are usually assumed, in practice, to be compensated for by depositional gains (atmospheric water vapor converted directly to ice crystals on the snowpack) of moisture.

At the end of October, 1966, Yellowknife Airport meteorological station reported one inch of snow accumulated on the ground.⁸ This indicates that only about one-tenth of an inch of the water equivalent precipitation that fell during the month of October was detained on the ground and contributed to the total seasonal snow cover at the Airport. Therefore, a refined estimate (compared to that of the Thornthwaite and Mather estimate) of the snow accumulation for the 1966-67 season is 3.1 inches of water equivalent at the Yellowknife Airport.

Snow Course Measurements

On January 1, 1968, the Yellowknife Airport meteorological station personnel began taking weekly snow measurements on a five sample snow course. The course site was changed during the summer of 1966, so only the first full season of readings, 1966-67, and the new site will be

⁸Canada, Monthly Record, October 1966, p. 15; also the entry for November 1, 1966, in the Snow Course Records made by the Canadian Department of Transport, Meteorological Branch, Yellowknife Airport stated "insufficient snow cover for survey."

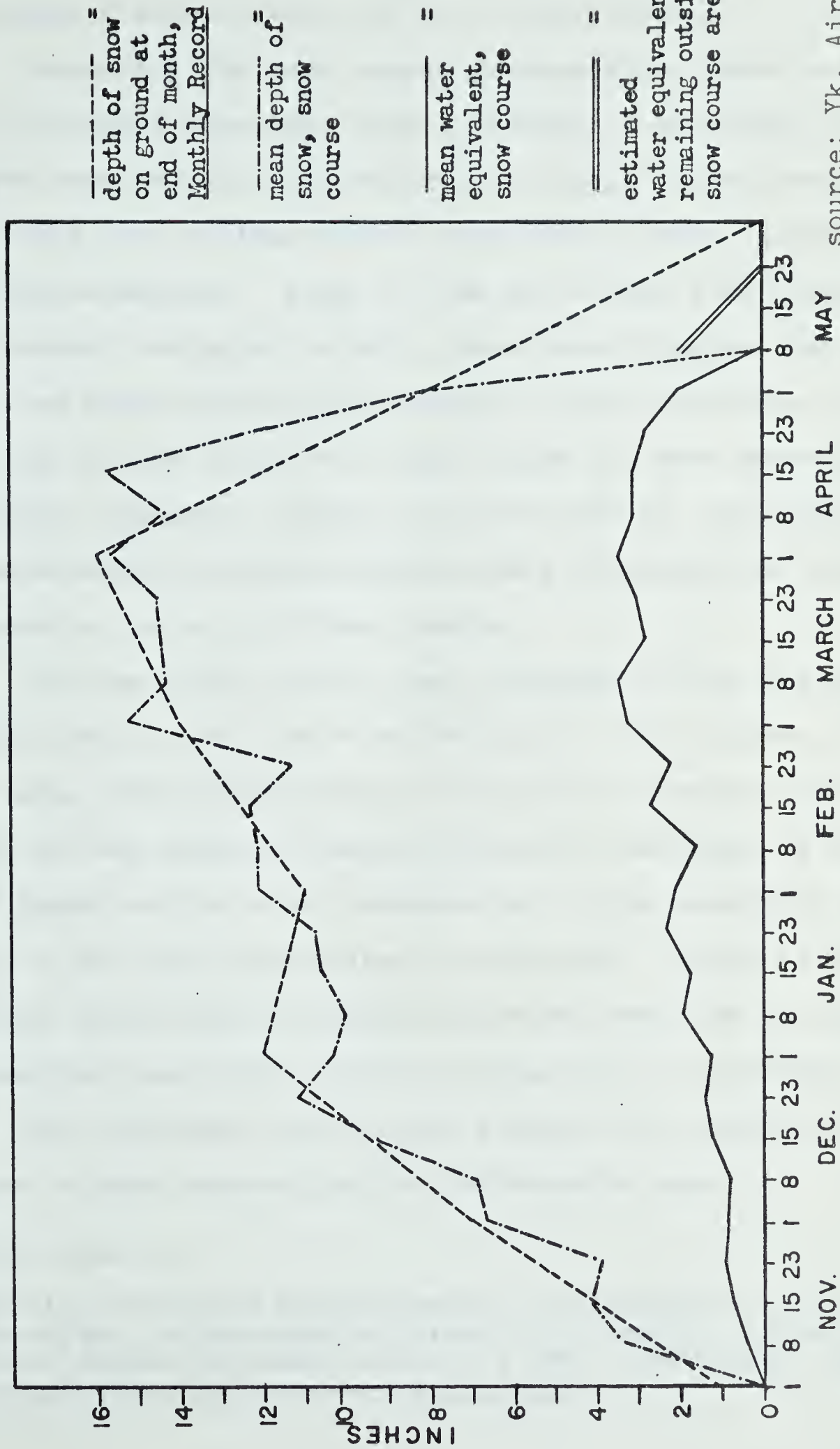
discussed here. From a snow sampling observation program, it is possible to obtain information about the duration of the snow cover, depth of snow accumulation, density of snow, and the water equivalent of the snow cover detained on the ground surface.

The M.S.C. Snow Sampler, Type I, was used for the snow sampling program. The snow course was laid out on a flat stretch of ground about 400 feet northeast of the Air Terminal Building, or just beyond the meteorological instrument area, and extended eastward for another 400 feet. It was at least 300 feet removed from any buildings or snow removal operations. The terrain of the course was very similar to the Airport site itself in that it was a flat, gravel covered pad with no wind obstructing vegetation nearby. In this respect, the course was not typical of the general terrain in the Yellowknife Area and therefore, the snow cover properties would also be dissimilar. However, the course measurements do provide important, additional information about the snow cover variables.

Figure 3-2 is a graph of the mean snow depth and water equivalents for the five sampling points of the snow course as they were measured through the snow cover season of 1966-67. Also, the depth of snow on the ground as measured at the Yellowknife Airport meteorological station at the end of each month is graphed.⁹ The two graph lines of snow depths agree

⁹The data for this graph were obtained from the

SNOW MEASUREMENTS FOR 1966-67 WINTER AT YELLOWKNIFE AIRPORT



source: Yk. Airport met. station records and Monthly Record

Figure 3-2

generally with the snow course values providing more detail of snow depth change through the snow cover season.

Regarding the snow course measurements, there are several perplexing occasions (e.g., February 1 and March 15) during the snow accumulation period when there was an increase in snow depth, but a simultaneous decrease in water equivalent of the total snowpack. Also, at the end of the snow accumulation period, but prior to melt, there were fluctuations in the amount of water equivalent detained in the snow cover. The drifting of snow could be a major cause of these anomalies. The writer suggests, however, that the end of the season maximum snow cover contained approximately 3.2 inches of water, as measured at the Airport snow course.

The measurable snow cover disappeared from the Meteorological Branch snow course by the May 8, 1967, survey. On this date, however, the Airport observer recorded a mean amount of two inches of water equivalent remaining in the snow cover based on his visual observation of the remaining snow cover in the area surrounding the Airport. On May 15 the estimate of one inch of water equivalent was made for the surrounding snow cover. This corroborates the previous statement that the course site at the Airport is unrepresentative of the terrain surrounding the Yellowknife Area.

original Snow Course Records made by the Canadian Department of Transport, Meteorological Branch, Yellowknife Airport, and were consulted there on May 17, 1967; and Canada, Monthly Record, October 1966 through April 1967.

In addition, during the early stages of the fall snow accumulation period (i.e., on October 26, 1966) the writer observed that Pocket Lake supported about five inches of smooth ice and that there was an average depth of approximately three inches of snow covering the lake and land surfaces near the outlet of the Lake. As mentioned earlier, the Yellowknife Airport meteorological station reported only one inch of snow depth on the ground at the end of October, 1966, and also, that there was not enough snow collected on the snow course site to survey on November 1, 1966. This also indicates that the Airport, and specifically, the snow course site differ from the generally rolling, Shield terrain of the Yellowknife Area with regard to snow detention.

Drifting

The two previous approaches to measuring snow (i.e., point measurements and mean snow course measurements) are both directed toward the elucidation of the average amount of snow received by, or collected at, a place. This type of value is used to compare widely separated places as to the general variations in the distribution of snow.

When factors that are influenced by the heterogeneity of the snow cover in a small area are considered, it is important to have additional information. The major disruption of the relatively uniform fall of snow is drifting. Because of dissimilar exposures to wind, land surfaces will detain very different amounts of snow. This is especially true, on

a relative basis, for areas of light snowfall.

Because of its solid state, snow can be detained on top of the ground surface, in excess of the field capacity of that surface, as long as temperatures remain below 32° F. Some very exposed surfaces are swept free of snow throughout the winter and thus, these surfaces will detain none of the winter's precipitation. Other more sheltered surfaces may provide receptacles for wind-blown snow and actually accumulate more than twice the mean winter snowfall for the general region.

When the snow precipitation is converted to liquid at the time of the spring melt, only that amount of water that can be indefinitely held against gravity by the soil particles or rock surfaces will be retained. The remainder will be removed from the area by gravitational forces in the form of surface or subsurface discharge. In spring, the exposed surface that detained no snow will be very dry and contribute no discharge. In fact, there will not be enough water to fill the spring retention capacity of the surface from the melting of snow. With regard to local conditions, that surface would have an early deficit in summer. Conversely, the drifted area will have a considerable amount of water liberated upon melting and the spring supply will exceed the amount of water that can be retained by the surface. Therefore, this area would not only have its retention capacity fully recharged, but would generate a surplus of water in spring.

These, then, are very different water balance conditions and the basic cause of their differences is the

irregular distribution of the snow cover, or input of precipitation, at the time of the spring melt. The irregular snow cover does not result from micrometeorological variations of snow precipitation, but from the relocation of snow by drifting over the ground surface after it has been precipitated. Therefore, the pattern of drifted snow in spring is an important factor of the water balance in the Subarctic.

1967 Water Equivalents in Pocket Lake Basin

Field Measurements

In order to investigate the spatial distribution of the snow cover in the vicinity of Yellowknife, a detailed field survey was conducted during the spring of 1967 in the Pocket Lake basin by the writer, with the assistance of Mr. L. P. Stene. An attempt was made to determine various aspects of the snow cover as they occurred over the 37.1 acre area. The areal unit of a drainage basin was selected because it is a natural unit which concentrates water surpluses from the area into a single outlet channel.

A total of 375 snow samples was taken in the area during the spring of 1967.¹⁰ A Mount Rose snow sampler was used. (See Figure 3-3.) With this instrument, the depth of snow can be read directly at each sampling site by a scale which is in inches and located on the outside of the coring tube. The

¹⁰The 1967 snow sample values and SYMAP coordinate locations for each sampling site are listed in Appendix A.

Figure 3-3. The Mount Rose type snow sampler. The inch calibrations on the outside of the coring tube indicate scale.

Figure 3-4. Sampling of a snowbank in Pocket Lake basin on May 20, 1967.



Figure 3-3.



Figure 3-4.

water equivalent of the sample is determined by weighing the tube, cradle, and core and then subtracting the weight of the empty tube and cradle. (See Figure 3-4.) The spring scale is calibrated in ounces, but because of the inside diameter of the tube (1.485 inches), the ounces of snow are directly equivalent to depth in inches of water. By dividing the depth of snow into the inches of water equivalent for any sample, the specific gravity (density) of the snow measurement is determined. Therefore, for each sampling site three factors of the snow cover were measured, i.e., snow depth, water equivalent, and specific gravity.

Of the 375 snow samples taken during the spring of 1967, ninety-six were obtained on April 28 and 29, and the remaining 279 were taken on May 9, 10, and 11. In addition to the sampling sites, photographs taken from the air were used in delimiting the areas of no snow cover. Also, field estimates of the area represented by a sampled water equivalent value were made and delimited on a large scale aerial photograph while the snow survey was being conducted. There was, therefore, considerable additional information obtained about the snow cover beyond that of the sample measurements.

The purpose of the intensive snow survey was to establish quantitative measures of the snow cover for the particular spring. The main object was not to begin collection of annual values that could be used as indices for following long-term trends of snow cover; however, the intensive survey and the basin melt pattern information (see later section of

this chapter) for Pocket Lake basin could be used to establish such an index snow course.

Field Map

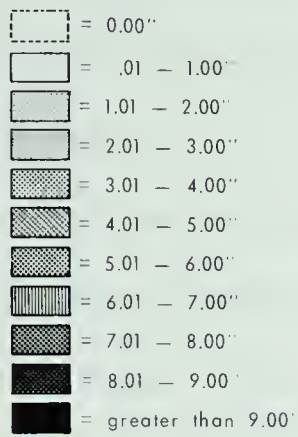

Map 3-1 is a detailed portrayal of the spatial distribution of the spring snowpack expressed in inches of depth of water equivalents. The map was drawn on the basis of the snow sample information, supplemented by field evaluations of the areal extent of each class. A one inch class interval was used to subdivide the water equivalent values. This constant class interval was selected for two reasons: 1) because it resulted in simple, even inch class intervals that were easily understood in the field, and 2) because the inch unit created the approximate number of data divisions that are perceivable in shades of gray on a map.

Snow cover is a continuous variable, but the intensity of the variations is great. It was found that the use of mapping techniques which portray continuous variation of the mapped data (contour lines or isolines) was impossible, even at the scale of the working base map.¹¹ For example, several situations occurred where a snowdrift of five or six or even ten inches of water equivalent had developed just in the lee of an exposed, wind-swept knoll. Actually the snow cover graded from zero to six or ten inches of water equivalent in,

¹¹The scale of the working base map was one inch equaled 100 feet, or two and one-half times the linear scale of Map 3-1.

FIELD MAP OF SNOW WATER EQUIVALENTS

Data Collected April 28-29 and May 9-11, 1967

POCKET LAKE BASIN
Yellowknife Area N.W.T., Canada
NORTH
Scale in Feet

pik

for example, ten horizontal feet on the ground. On the base map this would require six to ten contour lines in one-tenth of an inch distance. With the additional problem of reduction for the final maps, the general snow pattern would be obscured by lines.

Therefore, a type of dasymetric¹² representation, or something close to the proximal¹³ technique, was used for the Field Map. That is, the areal representativeness of each snow sample was estimated in the field. These unit areas were the basis for the Field Map (Map 3-1) rather than using the snow samples as point data and constructing isolines. In this manner, the data are depicted as a discontinuous variable, and adjacent areal units do not necessarily have consecutive values. In a few instances where severe local drifting occurred, adjacent values differ by as much as seven or eight classes.

The area of each encompassed unit on the map was calculated by counting the number of squares, one one-hundredth of a square inch in area, that covered the unit on the base map. The base map had a scale of one inch equals 100 feet,

¹²A. H. Robinson, Elements of Cartography (2nd ed.; New York: John Wiley and Sons, Inc., 1963), p. 174.

¹³The proximal mapping technique, as developed for the SYMAP program is based on the nearest neighbor idea for determining areal value portrayal on the map. The technique will be employed and discussed later in this chapter. For the Field Map, the mapped units are not developed on the nearest neighbor concept because field evaluations of the areal extent of each unit were used instead of merely developing the units from snow sample values.

and thus, the basic unit used for determining the areas amounted to 100 square feet of land surface. The areas for each class of snow water equivalent were grouped and tallied so that the class proportion of the total mapped area was determined. The percentage of each class was determined; multiplication of the per cent representation of a class by the class mid-point value of water equivalent yielded the amount of water retained in the basin for that class. Totaling these values for all classes gave a mean depth of 3.23 inches of water equivalent held by the snow cover over the entire basin. Figure 3-5 is a histogram of the frequency of each class, in per cent, as they occurred on the Field Map.

Interpretation of Field Map

It is felt by the writer that there are three factors that influenced the calculation of a basin mean water equivalent value from the 1967 Field Map. First, the majority of the lake surface was classed as detaining from 2.01 to 3.00 inches. Most of the samples taken on the lake were recorded as exactly three inches of snow water equivalent. Thus, the largest single unit on the map is calculated on the low side by about one-half inch.

Secondly, although the April 28 and 29 samples were taken prior to any significant melt, the May 9-11 measurements probably were preceded by some metamorphosis of the snow cover (i.e., surficial melting and refreezing at depth), and maybe even some slight melt with water entering the ground. In May,

FREQUENCY DISTRIBUTION OF AREA WEIGHTED 1967 WATER EQUIVALENTS FROM FIELD MAP

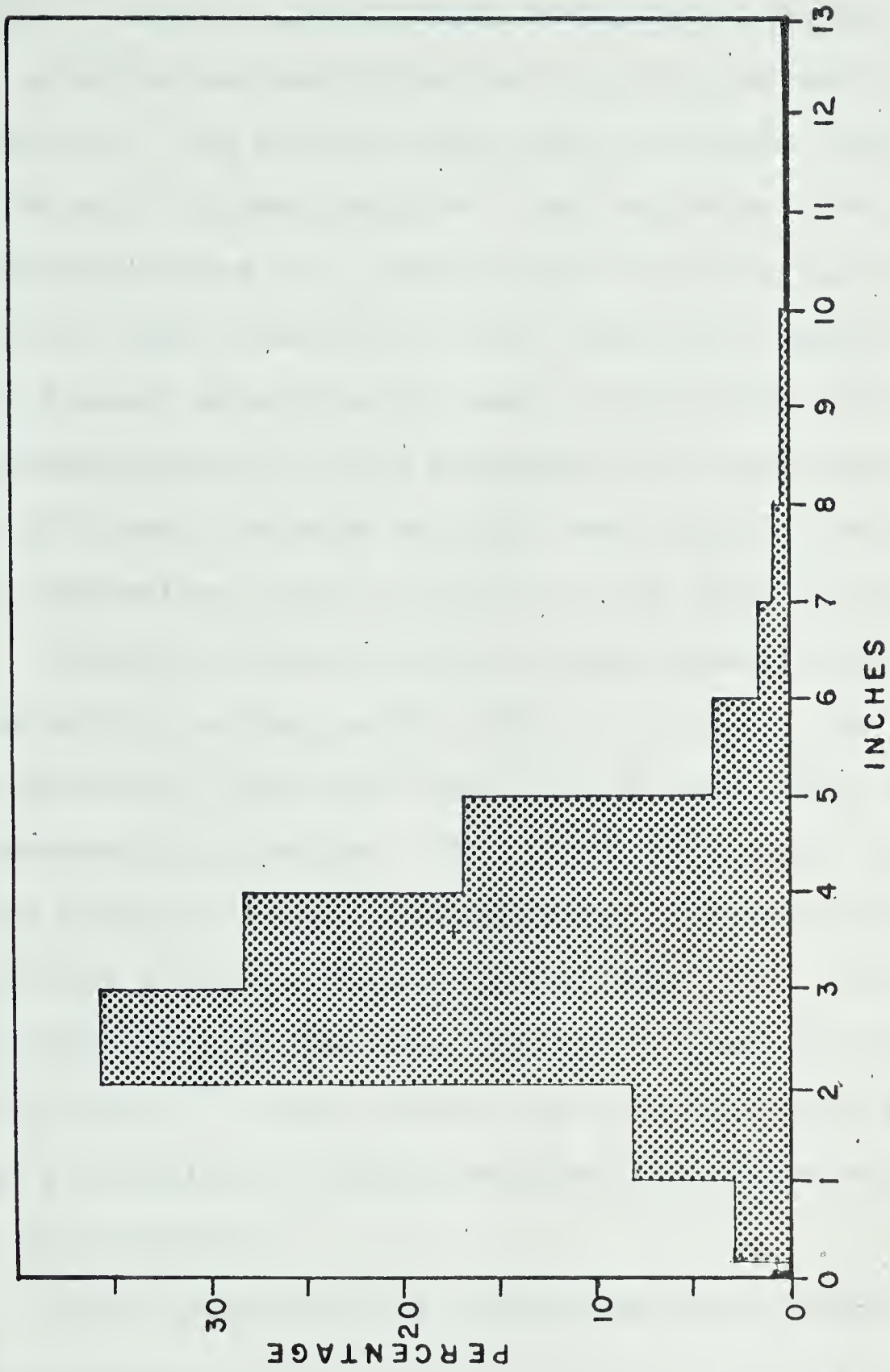


Figure 3-5

most of the deep drift areas were located and well sampled. The more extensive, lower value areas were sampled, but their areal coverage was determined to a greater extent by field estimations. The drifted areas did not change significantly from the April to May samples. The low value areas, however, were metamorphosed to a greater relative extent, and thus, because of their shallower depth, they had a higher probability of loss of snow cover by melt. Therefore, with the possible underestimation of the extensive low value areas, it is again felt that the area weighted mean depth of water equivalent determined from the Field Map is slightly low.

A third influence could be that some of the snow that melted before the May survey refroze on top of the lake ice or as basal ice under the land surface snow cover during the snow metamorphic process. This basal ice may not have been sampled properly in all cases because of the difficulty in identifying it (e.g., on top of the lake ice), and the difficulty of picking up the thin basal ice layer with the sampling tube.¹⁴ Thus, again, the Field Map may be slightly low in portraying the spring maximum snow water equivalent which was detained.

These influences all contribute to an underestimation

¹⁴When sampling the snow cover on Pocket Lake, it was noted that there was granular ice and ice lenses at the bottom of the snow layer, but it was impossible to determine where the original lake ice began and where the metamorphosed-refrozen snow ice stopped. Certainly the smooth lake ice surface and distinct snow-lake ice boundary that was observed by the writer on October 26, 1966, no longer existed.

of the maximum water held in the snow cover during the spring of 1967. Therefore, the writer believes that a more realistic mean value for the entire basin is 3.5 inches of depth of snow water equivalent. After corrections, the intensive snow measurements for the area of Pocket Lake basin are about 13 per cent higher than the Yellowknife Airport point measurements and almost 10 per cent greater than the mean snow course values for spring at the Yellowknife Airport.

The improvement of the measure of mean depth of snow water equivalent through the use of an intensive areal survey over a drainage basin is only slightly better than the previously discussed Yellowknife Airport measurements, because it is really only an improvement in the same type of measurements. That is, by reducing the areal survey to a mean value, it simulates a point measure that was obtained from a very large orifice catchment gauge (i.e., the area of the basin).

Spatial Relations

A more meaningful measure, and one of marked improvement in its application to the water balance, is the relation of the actual pattern of the spring snow cover to factors of the land surface where the snow has collected or has been removed. As explained previously, drifting is the reason why the precipitation received during the winter is not evenly distributed and does not approximate the mean value by the time of the spring melt.

There are two approaches to understanding the

relationship of drifted snow to ground surface types that will be discussed. These are: 1) the relation of ground surfaces to the detention or removal of snow during drifting, and 2) the relation of the water retention qualities of the ground surfaces to the amount of water released on these surfaces at the time of snow melt.

In comparing the Field Map of water equivalents for 1967 (Map 3-1) to the aerial photograph of Pocket Lake basin (Map 2-3), some relationships become apparent. First, the areas bare of snow are either very steeply sloping and rather smooth rock surfaces, or they are crests of the bedrock knolls. These surfaces apparently do not present enough resistance to the wind to detain snow.

Secondly, the surface conditions, where heavier than average snow cover develops, are generally areas with a distinct change in slope in a concave downward form. Most of the shore zone around Pocket Lake, and especially where the two gully-like systems open to the Lake on the southeast and south shores, accumulated large quantities of drifted snow. Also the margins of the several small, flat, marsh covered basins collected greater than average snow covers. The few areas of brush or low, stunted trees tended to correspond with moderately heavy snow accumulation. Therefore, surfaces which are removed from the full force of the wind and provide a depression where snow can collect, do accumulate rather large snowdrifts.¹⁵

¹⁵To some extent, the location of these drifts is

A third relationship of snow drifting to ground surfaces can be noted for the largest water equivalents, i.e., greater than 9.00 inches on Map 3-1. Most of these high value areas occur as small, isolated drifts that are generally surrounded by lower than average snow accumulation. These small, but deep, drifts probably develop from snow that has been blown only a short distance. Although this situation exhibits some of the most extreme variations in snow accumulation (e.g., from zero to over nine inches water equivalent in adjacent areas), the mean accumulation for the general area is not one of greater than average snow accumulation because of the offsetting low values surrounding a drift.

A fourth relationship can be mentioned in that the flat portion of the small, moss covered basins detained approximately three to four inches of snow water equivalent. In other words, these areas don't seem to have much unusual affect on snow drifting in that they accumulated about the mean snow cover.

To consider the relationship of the drifted snow cover to the retention of water by ground surfaces, a comparison is required of the Field Map of 1967 water equivalents (Map 3-1)

related to glaciation. As mentioned in chapter II, several observations in Pocket Lake basin indicated that the glacial ice moved over the area from the east-northeast. Since winds from the east are frequent in winter, the steep sides of the roches moutonnées (i.e., the plucked sides) provide better than average snow catchment areas. Certainly the steep, eastern shore of the Lake illustrates this relationship in addition to several small drift areas within the basin.

to the map of surface retention values for Pocket Lake basin (Map 2-5). The relation between these two variables is a matter of comparing snow accumulation on a surface to the amount of water that will be retained by that surface once the snow is melted in spring. The difference between the amount of water retained and the amount of snow detained yields the quantity of spring water surplus that will be generated from that particular surface. The total comparison of these two maps will result in an estimate of the total amount of surplus generated from the basin and also a quantitative evaluation of the surplus contributing areas within the basin. This will be done in detail and the results portrayed on maps later in this chapter, but first the mapping procedure is discussed.

The SYMAP Technique

The SYMAP, or computer mapping, technique was found to be a most effective means of spatially portraying the snow cover variables. It allowed flexibility in mapping techniques and facilitated the adjustments of data subdivisions. Computer mapping also reduced the subjectivity of mapping the collected data and speeded the cartographic process of dealing with several variables observed at multiple time periods. Therefore, the SYMAP program proved to be an important research tool to the geographical interpretation of the data in that numerous subdivisions of the data were readily displayed spatially for visual inspection. All of the maps programmed were analyzed; a series of three SYMAPs, each with different

modifications, were selected and presented for each set of values. Thus, the research advantage of multiple maps has been retained in this thesis in an attempt to provide a more thorough presentation of the data.

The SYMAP computer program was conceptually developed by H. T. Fisher in the fall of 1963 at the Northwestern Technological Institute, Illinois. The operational program is being further tested and modified at the Laboratory for Computer Graphics, Department of City and Regional Planning, Graduate School of Design, Harvard University, at the present time and is available from the Laboratory. The SYMAP input of:

Raw data of every kind (physical, social, economic, etc.) when given to the computer may be related, manipulated, weighted, and aggregated in any manner desired. By assigning values to the coordinate locations of data points or data zones, one or more of three basic types of map may be produced, as specified by the user.¹⁶

The nature of the collected snow cover data made it feasible to program two different types of SYMAPs. The familiar contour, or isoline, type of map illustrates the third dimension on a flat map surface by means of a series of closed curved lines that grade in value from high to low or vice versa. Each line connects all points of equal value, and between two contour lines a continuous gradation is assumed.

¹⁶Laboratory for Computer Graphics, "Reference Manual For Synagraphic Computer Mapping, SYMAP" Version V, Draft No. 2 (Cambridge, Mass.: Harvard University, Graduate School of Design, Department of City and Regional Planning, Laboratory for Computer Graphics, 1968), p. 5. (Xeroxed.)

Contour maps based on the data obtained from the snow sampling points were programmed.

The problem of using contours which was mentioned for the hand drawn Field Map was also encountered with the SYMAP print-out. Where data points were too close and their values too different, the output printer could not fit all of the different characters between the data points to show the continuous gradation. In these cases, the printer would break one or more contour lines at the constricted point. In following the contour gradations from one data point to the other, therefore, there might be one or more contour lines missing where the mapped values varied intensively.

With the intensity of the variations of the snow cover in Pocket Lake basin at the scale of the working base maps, it was felt by the writer that another type of SYMAP could provide additional information about the spatial pattern of the snow cover. Therefore, the proximal type map was programmed. The proximal mapping technique is dependent upon the proximity of surrounding areas to data points. The value of the area closest to any one data point is allocated the same class value as the data point. Thus, adjacent areas can jump in value from a low class to a high class with no indication of the intervening middle classes. This then, is a technique for mapping a discontinuous variate, but applied to snow cover because of the intensity of the value changes. In most cases, with irregularly spaced data points, the spatial units will also be irregular in shape and they "are defined by nearest

neighbor methods from point information. Each character location on the output map is assigned the value of the data point nearest to it."¹⁷ The data points themselves are the numerical characters corresponding to the data class number (symbol for class ten is F). The data point coordinates are listed in Appendix A; the row and column scales are printed as the SYMAP borders.

The greatest utility of SYMAP occurs when numerous maps are desired and some factors of each map are held constant. Constant factors usually include the outline of the mapped area (the A-OUTLINE package for the SYMAP program), the location of sampled values (B-DATA POINTS package), and the general explanatory and locational information necessary on the map (C-LEGEND package). With these factors constant, a set of measurements (E-VALUES package) corresponding to the appropriate data points can then be mapped by different techniques (e.g., contour and proximal type maps). Considerable manipulation of the data can be achieved by programming additional electives in the F-MAP packages which instruct the computer to make specific maps of the preceding data.

April Water Equivalent SYMAPs

The outline of Pocket Lake basin, general legend information, and the 1967 snow sampling points were digitized for the SYMAP program. Map 3-2 is a series of three computer maps based on the ninety-six water equivalent samples taken on April 28 and 29, 1967. Identical values and data points were used for all three maps in the series, however the

¹⁷Ibid., p. 7.

Legend for Map 3-2

WATER EQUIVALENTS, APRIL 28-29, 1967

MOUNT ROSE TYPE SNOW SAMPLER USED
BY LARRY STENE AND PETER KAKELA.

DATA VALUE EXTREMES ARE
INCHES OF WATER EQUIVALENTS

0.0

9.00

A
(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.0	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01
MAXIMUM	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01	9.00

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

11.22	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.00
-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9
SYMBOLS	1	2	3	4	5	6	7	8	9
FREQ.	2	3	19	26	24	11	6	3	2

B
(Proximal Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.0	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01
MAXIMUM	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01	9.00

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

11.22	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.00
-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9
SYMBOLS	1	2	3	4	5	6	7	8	9
FREQ.	2	3	19	26	24	11	6	3	2

C
(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

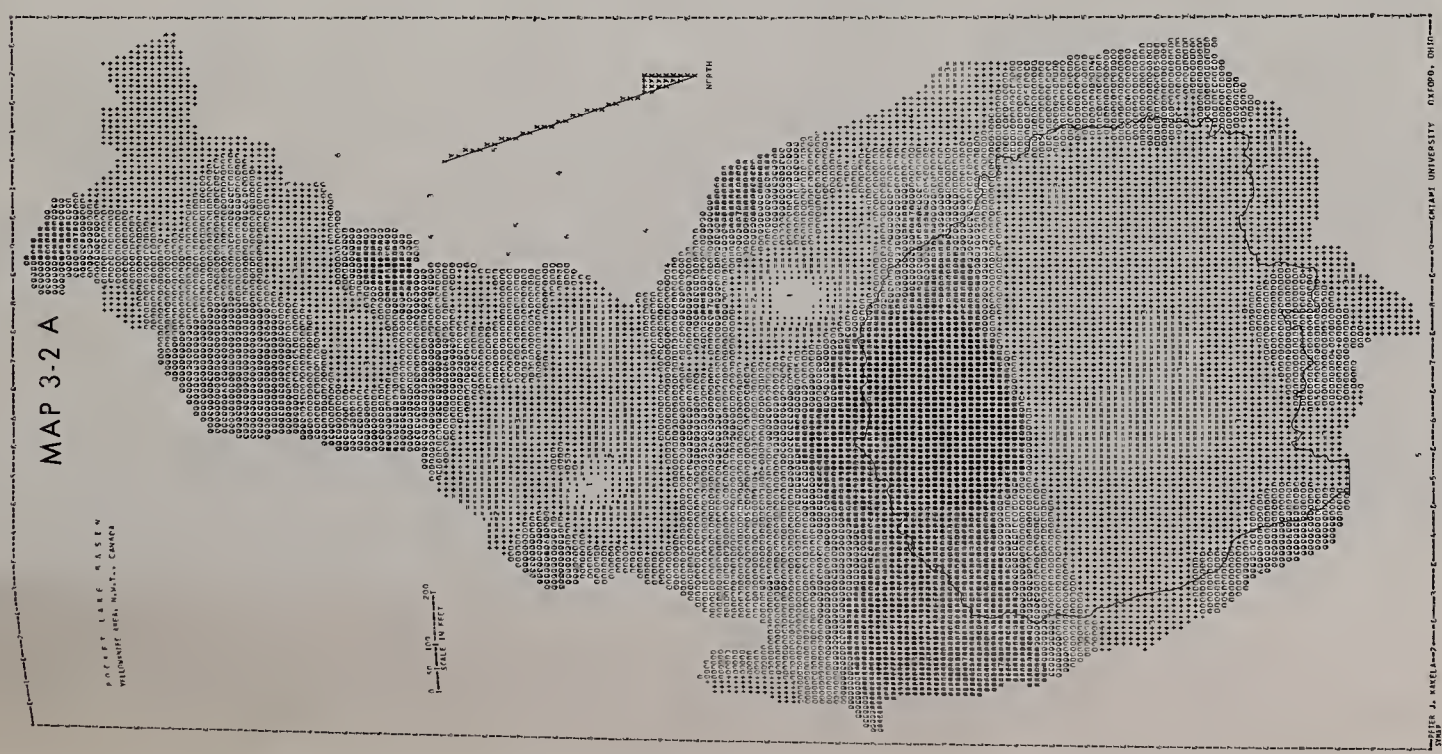
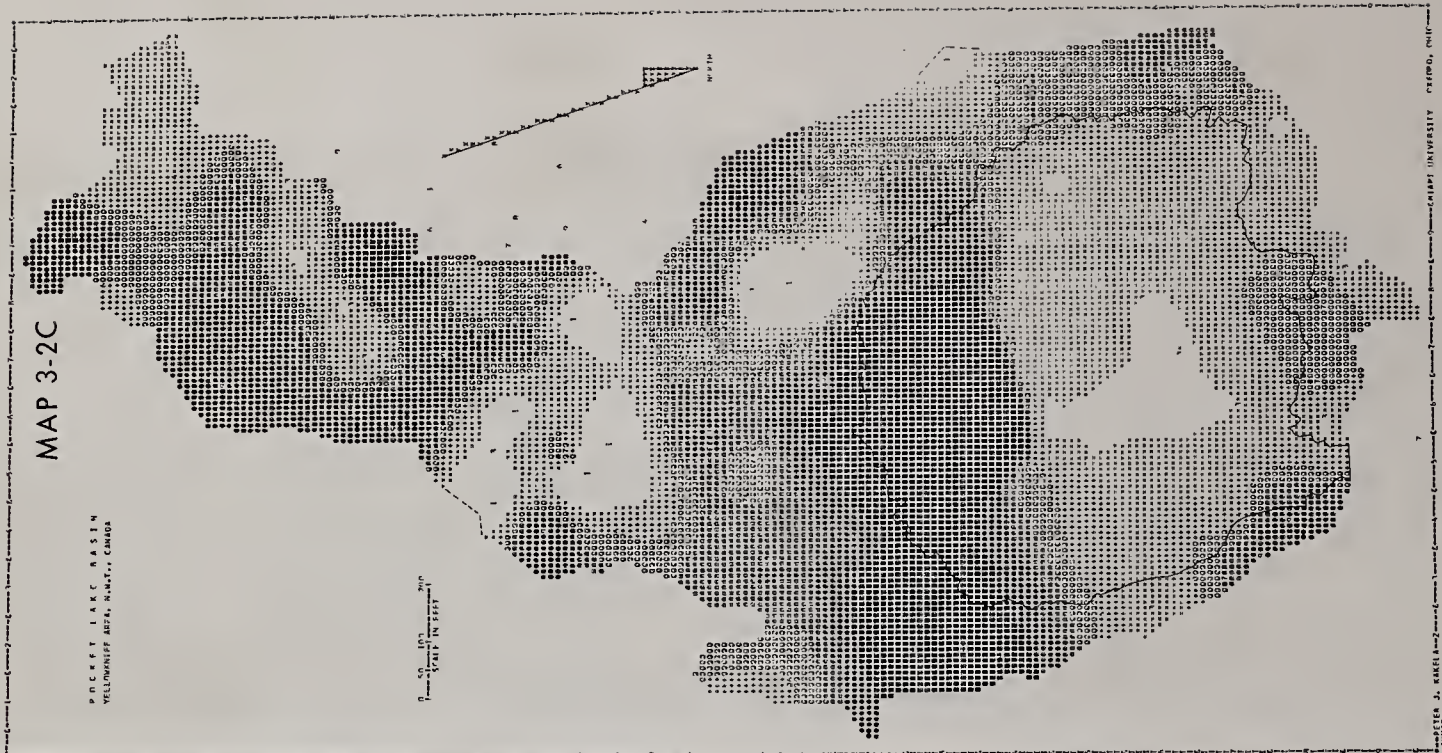
MINIMUM	0.0	3.00	3.00	3.50	4.00	4.00	4.50	5.00	5.50	6.50
MAXIMUM	3.00	3.00	3.50	4.00	4.00	4.50	5.00	5.50	6.50	9.00

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

33.33	0.0	5.56	5.56	0.0	5.56	5.56	5.56	5.56	11.11	27.78
-------	-----	------	------	-----	------	------	------	------	-------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	8	0	16	11	0	15	15	9	11	11



employment of different types of maps or data manipulation causes the different spatial presentations.

Map 3-2 A is a contour type map with a constant one inch interval between each of the nine classes, i.e., the classes change by an arithmetic progression. These classes are therefore of the same intervals as the Field Map of snow water equivalents (Map 3-1). It is apparent that the frequency of the sampling point values is definitely concentrated toward the middle values, especially from two through five inches of water. The map itself also indicates a concentration of mapped area in the middle value range by its overall gray tone, rather than a light, or a dark, or a contrasting tone.

Map 3-2 B is a proximal type map of the same values and identical classes as Map 3-2 A. The individual zones on the proximal map are rather large because of the limited number of data points. The proximal areas indicate a non-continuous variation of data from zone to zone. There is a similarity of pattern between the contour type and the proximal type maps. However, the proximal map has a slightly larger area designated as the highest class of values and also somewhat more area in the lowest class compared to the mid-range values.

Map 3-2 C is again a contour type map based on the same data point values as the two previous maps, but the values have been manipulated into different classes by using

a random progression. On this map, ten classes¹⁸ (the maximum number available with SYMAP) were attempted and the computer was instructed to divide the data so that approximately the same number of data points would occur in each class. Because of the nature of the raw data, only eight classes materialized.¹⁹ In spatial portrayal, Map 3-2 C very strongly emphasizes the data extremes and spreads out the high frequency mid-values. This is indicated by the fact that 33 per cent of the range of the data were included in the lowest class, 28 per cent in the highest class, and about 6 per cent in each of the middle classes. In tone, the map has much more contrast than the other two maps in the series. The

¹⁸ Robinson, in Elements of Cartography, p. 177, points out that the human eye can only distinguish six to eight different shades of gray. With the present maps, ten classes have frequently been used for four reasons: 1) snow water equivalents for Pocket Lake basin range from one to thirteen inches in 1967 and one to ten inches in 1968, so that ten classes with one inch intervals tended to separate most of the values, 2) white was used for the lowest category and black for the highest which technically reduces the number of "shades of gray" to eight, 3) different character symbols were used in each class which aids the eye in distinguishing tonal values, and 4) with more classes the raw data will be displayed in a more refined pattern.

¹⁹ The snow data were collected to the nearest one-half inch, thus the data points occurred only at the inch and half inch values. When the computer develops classes with equal frequency, it keeps a running total of the frequency rate. When the next group of values cannot be divided, but it is much too high for one class frequency, the class will not be developed. The following class will extend as far as necessary to encompass twice the normal class frequency of data points so that the mean level will be maintained. For Map 3-2 C, therefore, the computer deleted two classes because they would have caused undue weighting of the data toward the low values if they would have been developed.

benefit of this map is that it accentuates the extremes and gives an impression of where the values of water equivalent occur on a relative basis, i.e., where the higher and the lower than mean values are located.

In general, this series based on the limited April sampling depicts the water equivalents in too simplified a pattern over the basin when compared to the more detailed Field Map. Some trends of the patterns are similar, but the errors are most obvious for the Lake area. With a rather uniform snow cover, the Lake was not sampled as intensively at any time as the rest of the basin. The April survey included a single traverse of the Lake from the north shore to the west shore. Other measurements taken around the shoreline were extended erroneously over large, adjacent portions of the Lake surface by the computer with mathematical accuracy. The one large, high value area along the south shore is much too large and other exaggerations of high value areas have caused the overestimation of the mean snow water equivalent for the basin.

May Water Equivalent SYMAPs

The 279 snow samples of water equivalents taken on May 9, 10, and 11, 1967, were used for the Map 3-3 series. Map 3-3 A is a contour map in which an inch interval is used between each of the first nine classes. The tenth class is larger than the other classes (i.e., four inches) in order to include the greater maximum value of thirteen inches measured

Legend for Map 3-3

WATER EQUIVALENTS ,MAY 9-11, 1967

MOUNT ROSE TYPE SNOW SAMPLER USED
BY LARRY STENE AND PETER KAKELA.

DATA VALUE EXTREMES ARE 0.0 13.00
INCHES OF WATER EQUIVALENTS

A (Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.0	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01	9.01	10.01
MAXIMUM	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01	9.01	10.01	11.01

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

7.77	7.69	7.69	7.69	7.69	7.69	7.69	7.69	7.69	7.69	7.69	7.69
------	------	------	------	------	------	------	------	------	------	------	------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10	11
SYMBOLS	1	2	3	4	5	6	7	8	9	10	11
FREQ.	1	7	23	72	68	56	27	9	8	3	2

B (Proximal Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.0	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01	9.01	10.01
MAXIMUM	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01	9.01	10.01	11.01

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

7.77	7.69	7.69	7.69	7.69	7.69	7.69	7.69	7.69	7.69	7.69	7.69
------	------	------	------	------	------	------	------	------	------	------	------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10	11
SYMBOLS	1	2	3	4	5	6	7	8	9	10	11
FREQ.	1	7	23	72	68	56	27	9	8	3	2

C (Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

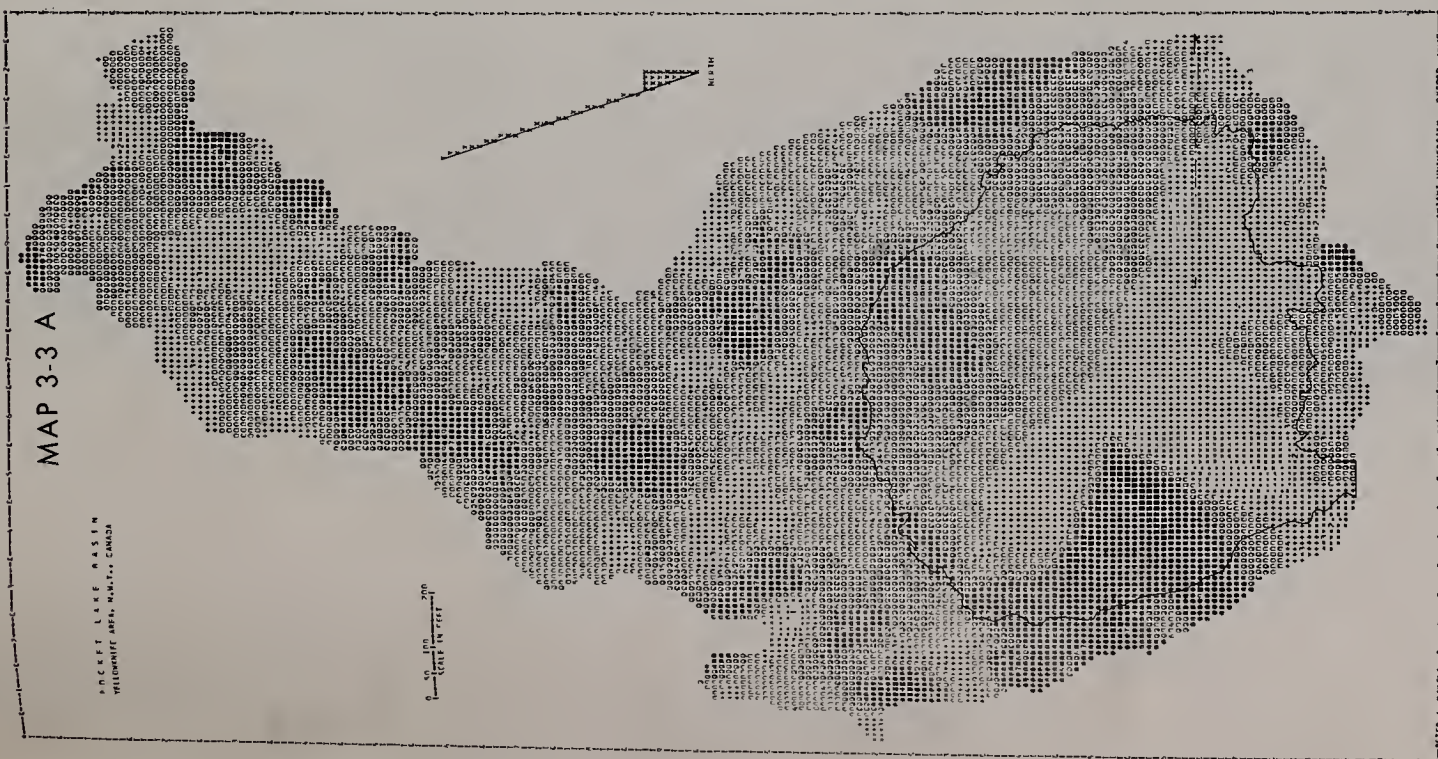
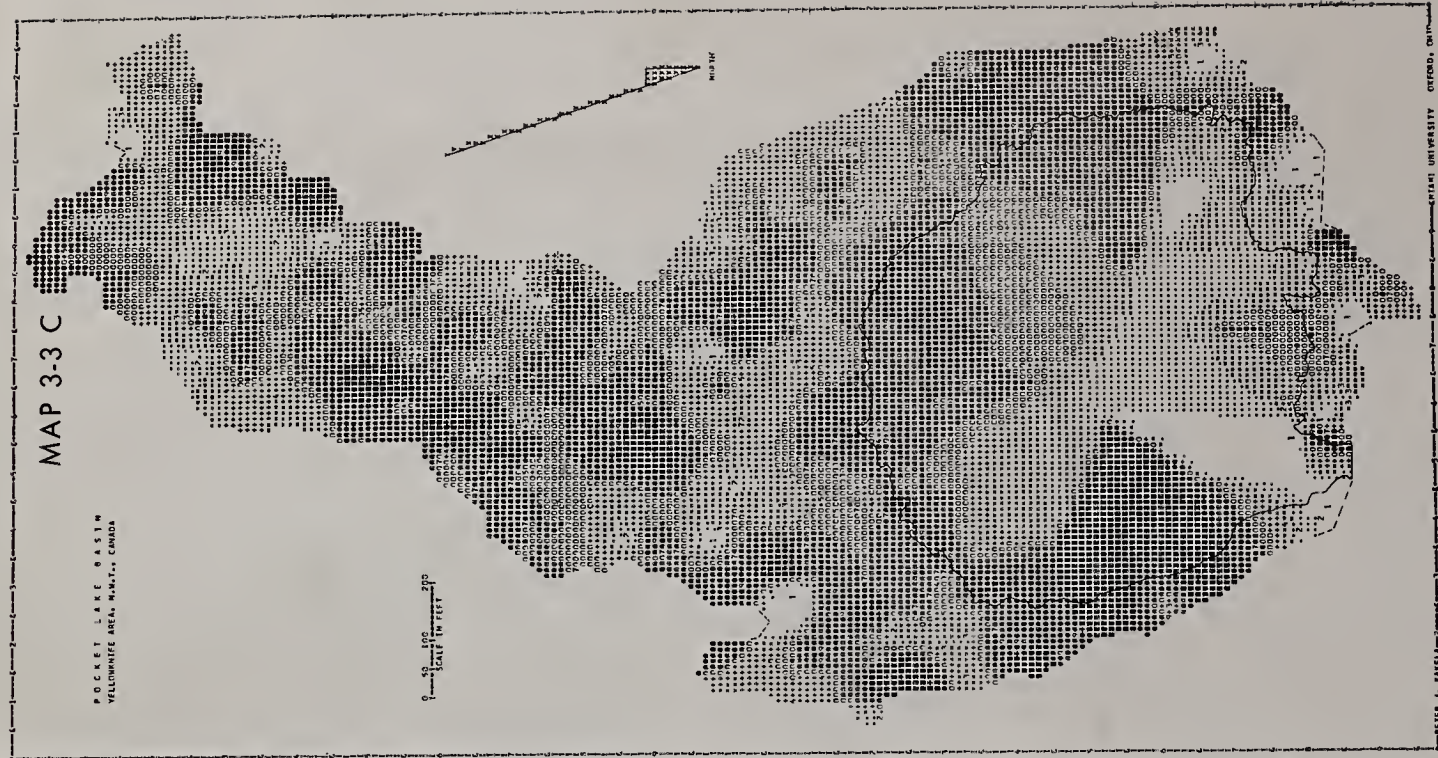
MINIMUM	0.0	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50	7.00	7.50
MAXIMUM	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50	7.00	7.50	8.00

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

23.08	3.95	3.85	3.85	3.95	0.0	7.69	0.0	7.69	0.0	7.69	4.15
-------	------	------	------	------	-----	------	-----	------	-----	------	------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10	11
SYMBOLS	1	2	3	4	5	6	7	8	9	10	11
FREQ.	15	16	27	45	26	0	64	0	45	41	0



in May, as opposed to the maximum of nine inches water equivalent measured in April. The greatest frequencies of May data point values are in the classes extending from three through six inches of water equivalent. This is a shift of one inch toward higher values when compared to the April measurements. In May there was again a disproportionately small number of snow samples taken on the Lake surface because of its relatively uniform snow cover. Without other input, the computer extended shore measurements onto the Lake too extensively when compared to the Field Map.

Map 3-3 B is a proximal map with the same values and class arrangement as the previous map. The discontinuous portrayal tends to visually and areally stress the small pockets of high values scattered throughout the basin. It distinctly depicts the single no snow cover value that was supplied at a sampling point. However, other no snow cover areas were identified from photographs and field observations and not designated as data points. Therefore, there is some tendency toward representing the data too high rather than too low.

Map 3-3 C is a contour presentation of the same data, but employing a random progression of class intervals so that approximately equal data points are included in each class. Two of the programmed ten classes were deleted because of the nature of the data. The map shows the relative distribution of snow water equivalents according to the May measurements, putting much more emphasis on the low and high values than do

the previous maps in the series. This can be illustrated by noting the per cent of the data range that is included in the lowest class (23 per cent) and the highest class (46 per cent), whereas the middle classes contain about 4 per cent each.

Although quite a different distribution is presented in the May series than in the April series of maps, both illustrate some factors of the distribution of snow water equivalents. The May series is based on more data points and is a more complex pattern. The combination of both sets of data seems obvious for a more accurate map of the 1967 situation.

SYMAPs of Combined 1967 Measurements

The combined snow sample values for water equivalent that were obtained during the spring of 1967 provide the input data for the Map 3-4 series. The contour map employing inch class intervals (except for the highest class) is Map 3-4 A; it shows a considerable refinement over the two previous maps of similar construction (Map 3-2 A and Map 3-3 A). The high value pockets are rather accurate in location and areal presentation, but there is still some distortion of the Lake shore high values in their extension toward the center of the Lake. The low values are not represented as numerous as they are on the Field Map (Map 3-1). The three classes with the highest frequency of data points falling within them include water equivalents of three inches through six inches. Because of the concentration of values in the mid-range,

Legend for Map 3-4

WATER EQUIVALENTS, APRIL 28-29 and MAY 9-11, 1967

MOUNT ROSE TYPE SNOW SAMPLER USED
BY LARRY STONE AND PETER KAKELA.DATA VALUE EXTREMES ARE
INCHES OF WATER EQUIVALENTS

0.0

13.00

A
(Contour Type Map)ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

	0.0	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01	9.01	10.01
MINIMUM	0.0	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01	9.01	10.01
MAXIMUM	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01	9.01	10.01	11.01

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

	0.0	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01	9.01	10.01
PERCENTAGE	7.77	7.69	7.69	7.69	7.69	7.69	7.69	7.69	7.69	7.69	20.69

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	3	10	42	98	92	67	33	12	10	9

B
(Proximal Type Map)ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

	0.0	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01	9.01	10.01
MINIMUM	0.0	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01	9.01	10.01
MAXIMUM	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01	9.01	10.01	11.01

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

	0.0	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01	9.01	10.01
PERCENTAGE	7.77	7.69	7.69	7.69	7.69	7.69	7.69	7.69	7.69	7.69	20.69

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	3	10	42	98	92	67	33	12	10	9

C
(Contour Type Map)ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

	0.0	3.00	3.50	4.00	4.50	5.00	5.50	6.00	7.00	12.00
MINIMUM	0.0	3.00	3.50	4.00	4.50	5.00	5.50	6.00	7.00	12.00
MAXIMUM	3.00	3.50	4.00	4.50	5.00	5.50	6.00	7.00	12.00	13.00

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

	0.0	3.00	3.50	4.00	4.50	5.00	5.50	6.00	7.00	12.00
PERCENTAGE	23.09	3.85	3.85	0.0	3.85	3.85	3.85	3.85	7.69	47.15

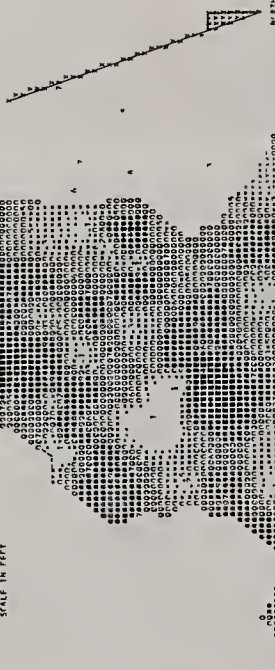
FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	23	32	38	0	60	41	51	31	57	47

MAP 3-4 C

POCKET LAKE BASIN
YELLOWSTONE AREA, WYOMING, CANADA

0 100 200
METERS

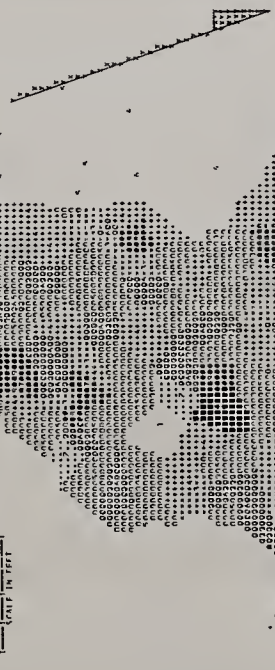


STATE OF WYOMING
STATE OF CANADA
STATE OF MONTANA
STATE OF IDAHO
STATE OF NEVADA
STATE OF UTAH
STATE OF ARIZONA
STATE OF NEW MEXICO
STATE OF TEXAS
STATE OF OKLAHOMA
STATE OF KANSAS
STATE OF MISSOURI
STATE OF ILLINOIS
STATE OF INDIANA
STATE OF OHIO
STATE OF PENNSYLVANIA
STATE OF MARYLAND
STATE OF DELAWARE
STATE OF VIRGINIA
STATE OF NORTH CAROLINA
STATE OF SOUTH CAROLINA
STATE OF GEORGIA
STATE OF ALABAMA
STATE OF LOUISIANA
STATE OF MISSISSIPPI
STATE OF ALABAMA
STATE OF FLORIDA
STATE OF ARIZONA
STATE OF NEW MEXICO
STATE OF TEXAS
STATE OF OKLAHOMA
STATE OF KANSAS
STATE OF MISSOURI
STATE OF ILLINOIS
STATE OF INDIANA
STATE OF OHIO
STATE OF PENNSYLVANIA
STATE OF MARYLAND
STATE OF DELAWARE
STATE OF VIRGINIA
STATE OF NORTH CAROLINA
STATE OF SOUTH CAROLINA
STATE OF GEORGIA
STATE OF ALABAMA
STATE OF LOUISIANA
STATE OF MISSISSIPPI
STATE OF ALABAMA
STATE OF FLORIDA

MAP 3-4 B

POCKET LAKE BASIN
YELLOWSTONE AREA, WYOMING, CANADA

0 100 200
METERS



STATE OF WYOMING
STATE OF CANADA
STATE OF MONTANA
STATE OF IDAHO
STATE OF NEVADA
STATE OF UTAH
STATE OF ARIZONA
STATE OF NEW MEXICO
STATE OF TEXAS
STATE OF OKLAHOMA
STATE OF KANSAS
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STATE OF ILLINOIS
STATE OF INDIANA
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STATE OF DELAWARE
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STATE OF INDIANA
STATE OF OHIO
STATE OF PENNSYLVANIA
STATE OF MARYLAND
STATE OF DELAWARE
STATE OF VIRGINIA
STATE OF NORTH CAROLINA
STATE OF SOUTH CAROLINA
STATE OF GEORGIA
STATE OF ALABAMA
STATE OF LOUISIANA
STATE OF MISSISSIPPI
STATE OF ALABAMA
STATE OF FLORIDA

MAP 3-4 A

POCKET LAKE BASIN
YELLOWSTONE AREA, WYOMING, CANADA

0 100 200
METERS



STATE OF WYOMING
STATE OF CANADA
STATE OF MONTANA
STATE OF IDAHO
STATE OF NEVADA
STATE OF UTAH
STATE OF ARIZONA
STATE OF NEW MEXICO
STATE OF TEXAS
STATE OF OKLAHOMA
STATE OF KANSAS
STATE OF MISSOURI
STATE OF ILLINOIS
STATE OF INDIANA
STATE OF OHIO
STATE OF PENNSYLVANIA
STATE OF MARYLAND
STATE OF DELAWARE
STATE OF VIRGINIA
STATE OF NORTH CAROLINA
STATE OF SOUTH CAROLINA
STATE OF GEORGIA
STATE OF ALABAMA
STATE OF LOUISIANA
STATE OF MISSISSIPPI
STATE OF ALABAMA
STATE OF FLORIDA
STATE OF ARIZONA
STATE OF NEW MEXICO
STATE OF TEXAS
STATE OF OKLAHOMA
STATE OF KANSAS
STATE OF MISSOURI
STATE OF ILLINOIS
STATE OF INDIANA
STATE OF OHIO
STATE OF PENNSYLVANIA
STATE OF MARYLAND
STATE OF DELAWARE
STATE OF VIRGINIA
STATE OF NORTH CAROLINA
STATE OF SOUTH CAROLINA
STATE OF GEORGIA
STATE OF ALABAMA
STATE OF LOUISIANA
STATE OF MISSISSIPPI
STATE OF ALABAMA
STATE OF FLORIDA

the map is dominated by the middle gray tones, as is the Field Map.

A count of the number of characters printed in each class on Map 3-4 A was made and the per cent frequency of the area appropriated to each class was determined.²⁰ The area weighted per cent frequency was multiplied by the class midpoint to determine the amount of snow water equivalent over the basin that each class contributed. These values were totaled to give an area weighted mean depth of 1967 water equivalent over Pocket Lake basin of 4.70 inches. The value is more than an inch greater than the area weight mean depth of water equivalent determined from the Field Map.

Using another SYMAP of water equivalents, an attempt was made to see whether an enlargement of the print-out map would provide a more accurate display of the data by allowing more room between data points for contour gradations to be shown. The same counting and calculating procedure was followed for a map enlarged twice the linear distance (i.e., fifty inches long) or four times the area. The areas calculated from the enlarged map were compared to a map of the same size as the base map for Map 3-4 A (i.e., twenty-five inches by thirteen inches), but with the identical data and classes as the enlargement.

²⁰H. T. Fisher, Director of the Laboratory for Computer Graphics, Harvard University, indicated to the writer in a telephone conversation on July 22, 1968, that this same tedious calculation of mapped areas by class, and determining of the per cent of the total that each class comprises, is going to be incorporated in the next revision of the SYMAP program (Version VI) which should be available in the near future.

The area weighted mean water equivalent determined from the double enlargement was about 3 per cent lower than the smaller map. Thus, mere enlargement of the base map did not significantly improve the presentation of the data. Also, the additional computer time and area calculation time, along with further problems of reproduction for page size presentation, made such large maps impractical.

Using the same test map data as above, different class boundaries were mapped and the printed areas per class were counted to determine if this would lead to any improvement. The first class included values of snow from zero to one-half inch water equivalent, and the remaining nine class boundaries were spaced at one inch intervals. The mid-points of the new classes were, for the most part, on the whole inch. The area weighted mean water equivalent depth calculated from this map was not quite 3 per cent lower than the "standard" form of the map. Again, the difference was not deemed a significant improvement when time and comparability to the Field Map were considered.

The proximal map of the combined 1967 snow samples (Map 3-4 B) indicates more distinctly the high and low areas than does the contour map. It also has added refinement over the previous proximal maps because of the more numerous data points used. A class area count was made of this map and the mean depth of water equivalent determined from the map was 4.40 inches. This is more than 6 per cent reduction of the contour map mean depth which was based on the identical data

and classes. Mean values would suggest that the proximal type of map is slightly more accurate in depicting the spatial distribution of snow water equivalent even though snow cover is, in actuality, a continuous variable. Certainly, the locational errors of water equivalents are more easily spotted on the proximal map than on the contour map. Thus, proximal type maps have been included in most of the map series not only as another portrayal, but also as a slightly more accurate form.

Map 3-4 C is a contour map with random class intervals arranged so that the data points are distributed rather evenly among all of the nine resulting classes. This portrayal of extremes is fairly accurate for the snow accumulation pattern on the north and west portion of the Lake surface. It is helpful in locating areas of relatively high or low water equivalent values.

Comparison of SYMAP to Field Map

Judging from the mean values of snow water equivalent determined from the SYMAPs as compared to the Field Map, it might be stated that the SYMAP is not very accurate. The accuracy of the SYMAP program is really very great in a mathematical sense in that it precisely determines the locations of contour lines or proximal areas and carries the calculations to several decimal places.²¹

²¹This point was explained to the writer by A. H.

The inaccuracy of the present maps is caused by two types of factors: 1) mechanical print-out, and 2) data input. The mechanical print-out problems involve the limited refinement of the computer printer because of the typed character size (one-tenth by one-eighth of an inch in area). This problem can be circumvented by enlarging the print-out map considerably and subsequently reducing it for presentation, however the limited improvement of spatial portrayal was discussed previously. The data input factor is much more significant with respect to the present maps. The data input for the SYMAPs was limited to the snow sampling points, whereas the effective "input" for the Field Map was much more extensive in that much of the spatial pattern was estimated in the field at the time of snow sampling. The writer feels that an improvement of SYMAP input can be made by utilizing more generally the Field Map information and making certain adjustments to the poorly depicted Lake surface. An improved SYMAP of snow water equivalent will be of great importance in developing basin-wide relationships with regard to surface retention values and spring surpluses. Such a map is the focus of the following section.

Generalized Spring 1967 Water Equivalents

In an attempt to improve the spatial portrayal of the

Schmidt, Assistant Director, Laboratory for Computer Graphics, Harvard University, in a telephone conversation on July 15, 1968.

water equivalents in Pocket Lake basin, the Field Map (Map 3-1) data were generalized and used as input for a series of SYMAPs. The generalization was accomplished by superimposing a square grid system over the Field Map and calculating the mean depth of spring water equivalents for every 10,000 square feet of surface area.²² This mean depth was then used as the value for a data point located at the center of the square. A total of 192 regularly spaced data points resulted from the generalization process and provided the input for the Map 3-5 series. The nature of the data for the generalized maps is different from that of the previous SYMAPs in that the generalized data are mean values derived from an area, whereas the previous maps were drawn from points where individual samples were taken.

Contour Map 3-5 A presents the distribution of the generalized values according to class intervals set at the even inch boundaries of water equivalents. These classes are comparable with the divisions and map symbols used in Map 3-2 A, Map 3-3 A, and Map 3-4 A. In Map 3-5 A the data range was from 1.20 inches to 5.50 inches, and thus only five classes developed. Because of the generalizing process, the

²²More specifically, a grid with ten squares to the linear inch was overlaid on the base Field Map of water equivalents which had a scale of one inch equal to one hundred feet. For each square inch of the grid (i.e., 10,000 square feet of earth surface), the proportion of each water equivalent class was determined by counting the number of squares, one one-hundredth of a square inch in area, that covered that class. From these class proportions, the mean depth of water equivalent was determined for each square inch of the grid.

Legend for Map 3-5
GENERALIZED WATER EQUIVALENTS, 1967

WATER EQUIVALENTS OF SNOW COVER GENERALIZED FROM FIELD MAP TO MEAN DEPTH FOR 10,000 SQ. FT. AREAS. DATA VALUE EXTREMES ARE 1.20 5.50 INCHES

A
(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY					
MINIMUM	1.20	2.01	3.01	4.01	5.01
MAXIMUM	2.01	3.01	4.01	5.01	5.50
PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL					
	18.84	22.26	22.26	22.26	11.40

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL					
LEVEL	1	2	3	4	5
SYMBOLS	.....	=====	++++++	00000000	00000000
	.....	=====	++++++	00000000	00000000
	.....	=====	++++++	00000000	00000000
	.....	=====	++++++	00000000	00000000
	.....	=====	++++++	00000000	00000000
FREQ.	5	71	98	17	1

B
(Contour Type Map)

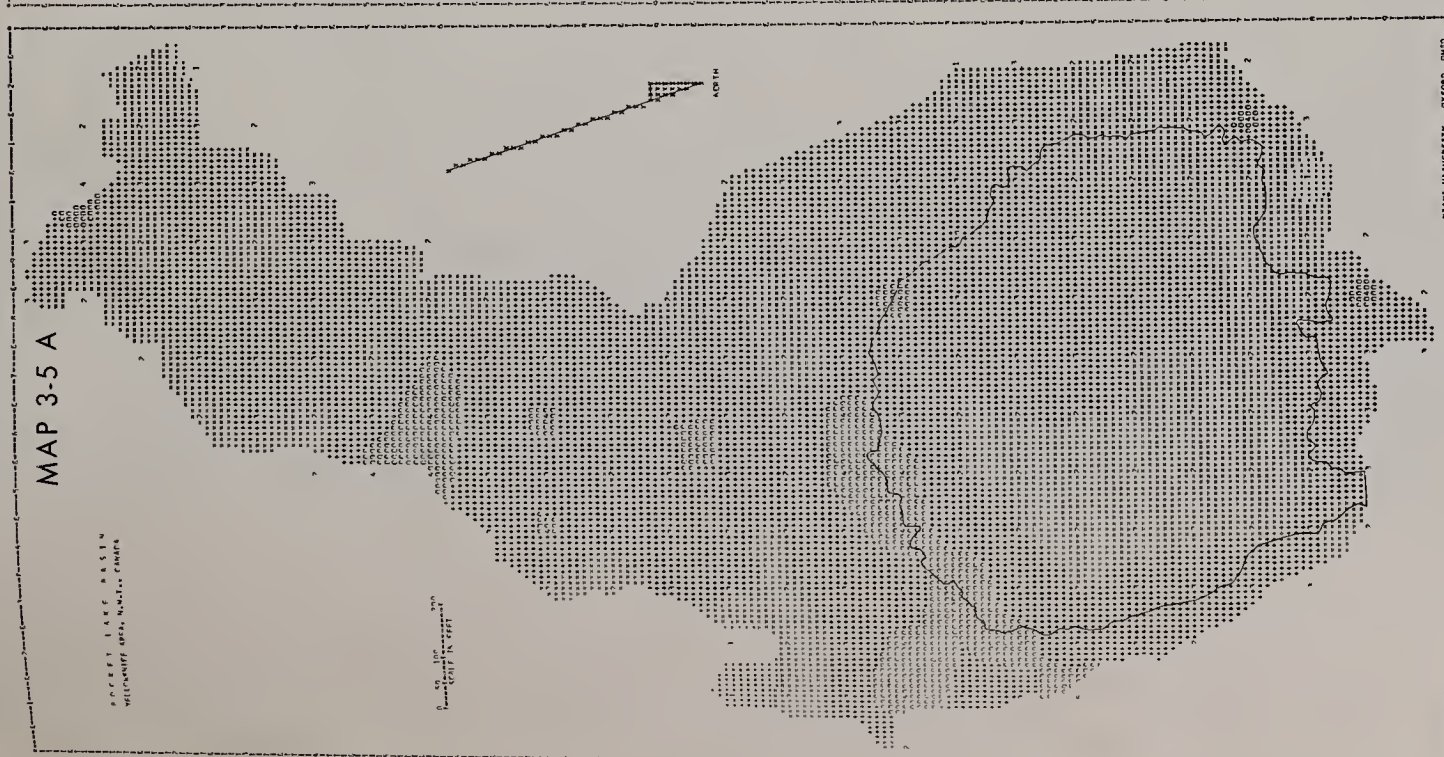
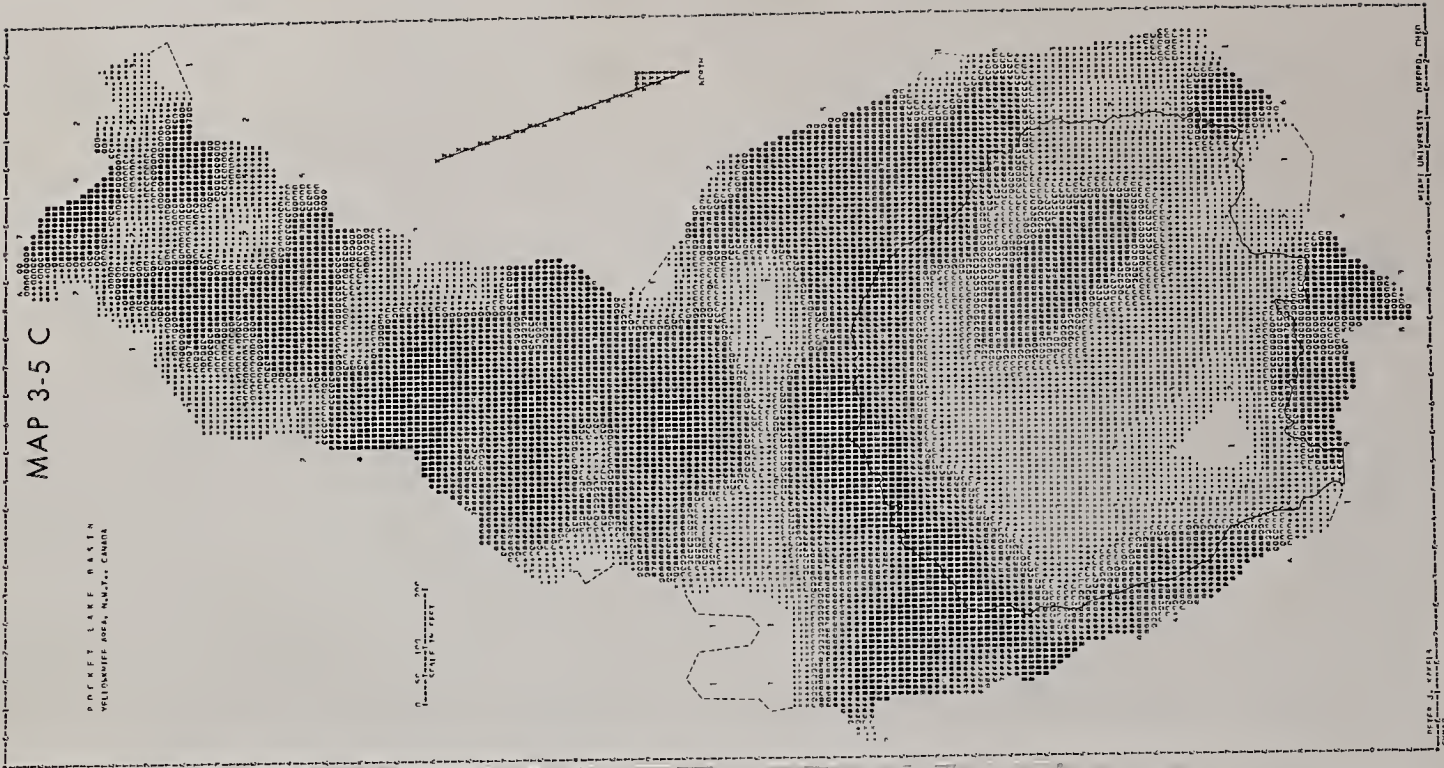
ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY										
MINIMUM	1.20	1.63	2.06	2.49	2.92	3.35	3.78	4.21	4.64	5.07
MAXIMUM	1.63	2.06	2.49	2.92	3.35	3.78	4.21	4.64	5.07	5.50
PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL										
	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL										
LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	.....	=====	++++++	00000000	00000000	00000000	00000000	00000000	00000000	00000000
	.....	=====	++++++	00000000	00000000	00000000	00000000	00000000	00000000	00000000
	.....	=====	++++++	00000000	00000000	00000000	00000000	00000000	00000000	00000000
	.....	=====	++++++	00000000	00000000	00000000	00000000	00000000	00000000	00000000
	.....	=====	++++++	00000000	00000000	00000000	00000000	00000000	00000000	00000000
FREQ.	3	2	10	38	62	35	27	10	3	1

C
(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY										
MINIMUM	1.20	2.50	2.90	3.00	3.10	3.20	3.30	3.50	3.80	4.00
MAXIMUM	2.50	2.80	3.00	3.10	3.20	3.30	3.50	3.80	4.00	5.50
PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL										
	20.23	6.98	4.65	2.33	2.33	2.33	4.65	6.98	4.65	24.88

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL										
LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	.....	=====	++++++	00000000	00000000	00000000	00000000	00000000	00000000	00000000
	.....	=====	++++++	00000000	00000000	00000000	00000000	00000000	00000000	00000000
	.....	=====	++++++	00000000	00000000	00000000	00000000	00000000	00000000	00000000
	.....	=====	++++++	00000000	00000000	00000000	00000000	00000000	00000000	00000000
	.....	=====	++++++	00000000	00000000	00000000	00000000	00000000	00000000	00000000
FREQ.	15	16	22	22	16	11	28	20	15	26



extreme values were averaged out and no values occurred in the lowest class (zero to one inch) or the highest classes (six inches or more) of the previous maps. Thus, Map 3-5 A has a nearly uniform gray tone with very little definition of high or low water equivalents.

To bring forth the spatial pattern of the generalized water equivalents, the data were subdivided into ten classes, each spanning 10 per cent of the data range. Map 3-5 B shows the distribution of these divisions by contours. The pattern of the heavier than average water equivalents is especially apparent from this map, whereas it was obscured on the previous map. A count of the printed characters in each class was made for this map, and an area weighted mean depth of 3.32 inches of water equivalent was calculated. This mean depth determined from the portrayal of the generalized water equivalent values is very close to the mean depth of water equivalents calculated directly from the Field Map (3.23 inches). Table III-1 summarizes the estimates of the 1966-67 snow water equivalents presented in the thesis.

Map 3-5 C is a contour type map of the generalized water equivalent values divided into ten random interval classes, each class contains approximately the same number of data points. Because the class intervals for this map tend to spread the data out toward the higher and lower classes rather than allowing it to remain concentrated in the middle classes, the map spatially stresses the lowest and highest classes. In fact, rather than dividing the data range into

10 per cent intervals as did the previous map, Map 3-5 C divides the area mapped into approximately ten equal spatial units, one unit occupied by each class. This results because every class contains about the same frequency of data points and because the data points are equally spaced on the map.

TABLE III-1

VARIOUS ESTIMATES OF 1966-67 MEAN SNOW COVER
WATER EQUIVALENTS IN YELLOWKNIFE AREA*

Procedure	Inches
Yellowknife Airport data, Thornthwaite and Mather's temperature boundary (30.2° F.)	4.56
Yellowknife Airport data, Adjusted Thornthwaite and Mather value	3.50
Yellowknife Airport data, snow on the ground	3.10
Yellowknife Airport snow course values	3.20
Field Map (3-1) of Pocket Lake basin	3.23
Refined Pocket Lake basin field estimates	3.50
Contour SYMAP (Map 3-4 A) of Pocket Lake basin	4.70
Proximal SYMAP (Map 3-4 B) of Pocket Lake basin	4.40
Generalized SYMAP (Map 3-5 B) of Pocket Lake basin	3.32

*The procedural base for each estimate is discussed in the foregoing text.

Based on mean depths, these generalized SYMAPs are fairly precise in their representation of the spring 1967

water equivalent data for Pocket Lake basin. These maps are suitable for spatial comparison to other water balance variables that can be transferred to the generalized grid units and mapped. Such maps and comparisons are presented in the succeeding portion of this chapter.

Relation of 1967 Water Equivalents to Spring Water Balance

Introduction

The foregoing maps provide the spatial portrayal of the 1967 spring accumulation of snow precipitation in water equivalents for Pocket Lake basin. This, then, is a measure of the spring input for the water balance of this area. If the various spring output factors of water are compared to the snow precipitation, the balance can be established. In so doing, information can be derived about the relationships between snow precipitation and such aspects as spring surplus, retention storage, and limitations of moisture supply. Through maps, these relationships can be developed spatially within the basin; these spatial relationships are the present objective.

Spring Output Factors of Water

Focus on the water balance relations in the spring was selected for intensive study for several reasons. First, because spring is the period when the accumulation of the winter's precipitation is being transformed into a dynamic

factor of the water balance. Secondly, the spring period is apparently the time when most surplus is originally generated in the Subarctic. And thirdly, spring is when temperatures are beginning to exceed freezing after a long duration of subfreezing conditions; enough heat is supplied to melt snow, but not enough to cause significant evaporation or transpiration. Therefore, from a water balance approach, spring in the Subarctic is a time when the compounded winter precipitation is being transformed into a dynamic, interacting commodity, but with only limited output possibilities.

Working on water balance relationships at a time when potential evapotranspiration is virtually nil is, in essence, like working with a partially controlled experiment. The elimination of the consideration of evapotranspiration is especially significant to Subarctic water balance relationships because (as mentioned in chapter I) the rate of potential evapotranspiration for high latitudes is one of the major possible errors of applying the Thornthwaite water balance to the Yellowknife Area. With this factor eliminated, the present study is focusing on the water balance relationships in the Subarctic when only the more distinct high latitude factors (e.g., snow cover and permafrost) are influencing these relationships.

The spring output factors then include additions to storage and surplus. The positive storage changes occur when spring meltwater is retained on rough rock surfaces or unsaturated, unfrozen soil surfaces. Spring surplus is generated

when detained snow water equivalents exceed retention capacities of any surfaces. In spring, it is possible for some surfaces to detain less snow than they could retain water, so when the snow is melted, not all of the retention storage capacity is filled with water. Thus, these surfaces would not receive complete storage recharge.

Basin Unit

In considering the spring water balance, the entire Pocket Lake basin can be regarded as a unit. At this scale the values for the water balance would be the mean values for the basin as calculated from the respective maps. Therefore, using formula 1.1, the 1967 spring water balance in inches for Pocket Lake basin would be:

$$3.23 = (0 - 0) + 2.40 + .83$$

As determined from the Field Map (Map 3-1), the mean 1967 spring snow depth over the basin is 3.23 inches and provides the input for the balance.

The spring quantities of output moisture must balance the mean snow precipitation. As stated previously, evapotranspiration at the time of snow melt is virtually²³ zero. Because there is no evaporational or transpirational demand

²³Some evaporation does occur during the spring snow melt as a result of specific conditions. The writer observed water temperatures as high as 55° F. in small puddles that collect in bedrock niches and have a black organic bottom layer while air temperatures four feet above the water surface were 33° F. These puddles on the bedrock surface were observed to decrease in volume on successive days during the melt.

on spring moisture, the supply cannot be less than the zero demand, and therefore deficits would virtually²⁴ not occur in spring. On a basin-wide basis, there is plenty of meltwater available in spring to supply the entire mean spring retention capacity of .83 inches depth as calculated from Map 2-5. This then, is an addition to moisture storage in the basin. In fact, there is considerably more snow water equivalent than can be retained and so the excess 2.40 inches will be surplus that originates from Pocket Lake basin during the spring of 1967. If the larger, estimated snow accumulation value was used (3.50 inches) the additional precipitation would be manifested as surplus output.²⁵

Change of Time Scale

The water balance components can vary in value when either the time scale or the areal scale is changed. One example of the change in relationships with the alteration of time is the difference between considering station data on a

²⁴ In practice, slight deficits do occur during the snow melt period as soon as rock surfaces dry off. These deficits are probably compensated for in quantity by the slight precipitation received during snow melt.

²⁵ Not all of the excess water will reach the streams in spring. Some of the melted excess will be changed from snow detention to detained water stored (in excess of the field capacity) in the moss covered areas, refrozen in the previously relatively dry, active layer overlaying permafrost, or detained in lakes. These detained surpluses of water would still have originated and been generated from spring snow melt, but would not be manifested as stream runoff until sometime later. This delaying of runoff is considered more fully in chapter IV.

mean annual basis as compared to a mean monthly basis. A second example of the influence of the time period is calculation of the water balance from long-term averaged mean monthly data versus the calculation of the water balance each year from mean monthly data and then averaging these individual yearly water balance values to derive the long-term means. In both of these examples, consideration of the water balance on the shorter time scale (i.e., monthly basis or individual yearly basis) yields more accurate estimates of the variables.

The refinement of the Thornthwaite estimation of water balance components by considering shorter time periods appears to have some optimum time interval. This interval appears to be longer than one day, but probably shorter than one month. The limitation to refinement through shorter time periods is caused by the relative increase in importance of other factors not considered in the Thornthwaite approach.

These compensating factors for which the Thornthwaite water balance does not allow include humidity and wind. For the monthly calculations these two factors are considered to "average out" for most mid-latitude locations. That is, there is seldom an exceptionally windy or calm month, nor is an entire month very often marked by abnormally high or low humidity. However, these abnormal wind or humidity conditions often persist for a day at a time.²⁶ Thus, these

²⁶ This point was made by J. R. Mather at the East

additional factors influence the daily water balance, but compensating errors from day to day tend to average out for many stations when long time periods are considered.

Change of Areal Scale

Introduction. It is thought by the writer that if the size of the areal unit is changed, refinements can be made in the location of and quantitative estimation of the water balance components. One large scale example of this refinement is A. H. Laycock's mapping of the regional variation of water surpluses²⁷ and deficits²⁸ for the Prairie Provinces of Canada. His maps portray the great variation of these water balance components within large drainage basins. Also, he showed that a small portion (12.2 per cent) of the North Saskatchewan River basin contributed most (81.3 per cent) of the total streamflow from the basin in a dry year.²⁹ On the Prairie scale, the variations of the water balance relationships were

Lakes divisional meetings of the Association of American Geographers held at University of Windsor on October 20, 1967.

²⁷ A. H. Laycock, "The Need for a Regional Approach in Watershed Management Planning," Proceedings of the American Water Resources Association (December, 1965), pp. 146-154; and A. H. Laycock, Water Deficiency and Surplus Patterns in the Prairie Provinces, Prairie Provinces Water Board Report No. 13 (Regina, Saskatchewan: Prairie Provinces Water Board, 1967), 187 pp.

²⁸ A. H. Laycock, Water Deficiency Patterns in the Prairie Provinces, Prairie Provinces Water Board Report No. 8 (Regina, Saskatchewan: Prairie Provinces Water Board, 1964), 51 pp.

²⁹ Laycock, "The Need for a Regional Approach to Watershed Management Planning," p. 147.

caused by greatly differing rates of precipitation plus moderately differing rates of potential evapotranspiration regionally.

In considering different areal scales for Pocket Lake basin, some refinement of the mean spring water balance can be achieved. The refinement would not be based on the location of areas with differing potential evapotranspiration rates because the variance is too small for such a limited area. Furthermore, as explained previously, the spring period is a time of virtually no potential evapotranspiration. The spatial variations are derived from differences in precipitation, not in amount received, but rather in the different accumulations of snow precipitation after drifting. In addition to the variable distribution of snow precipitation there are different rates of retaining the spring meltwater for different surface conditions. Within Pocket Lake basin both of these factors (maximum spring water equivalents and spring water retention) vary considerably from the basin mean value. Thus, there are numerous variations of the water balance relationships for the different surfaces throughout the basin.

If subdivisions of the basin are considered instead of the entire basin, attention can be directed toward some of the water balance variations that occur. To establish these variations, a separate spring water balance can be calculated for each subdivision as long as the snow precipitation and spring retention values can be determined for these units. This calculation of spring water balance has been done for

two different scales of subdivisions in Pocket Lake basin. The first scale was a generalization of the field established maps to a system of grid squares, each with an area of 10,000 square feet on the ground surface. (The Map 3-5 series of water equivalents was developed on the basis of this grid system.) The second areal division of the basin was based on all the detail of the field maps, and thus, was even more refined. These units were delimited by superimposing the Field Map (Map 3-1) over the Surface Retention Map (Map 2-5) and establishing detailed homogeneous units where boundaries on either map occurred. The results and evaluation of both of these areal refinements are presented here.

Generalized Surface Retention SYMAPs. The Surface Retention Map (Map 2-5) was generalized to the identical 10,000 square foot units as were the spring water equivalents, to permit the establishment of the other spring water balance components for each of the 192 resulting grid units. The calculation of the mean rate of surface retention for each generalized unit was determined in the same manner as were the water equivalents. The resulting data were used as input for a series of SYMAPs.

Map 3-6 A shows the generalized spring retention values subdivided into seven classes. These classes are identical to those of the detailed Surface Retention Map (Map 2-5), with the exception of the highest class (3.51 through 4.50 inches) which did not develop its full interval

Legend for Map 3-6

GENERALIZED SURFACE RETENTION

SURFACE RETENTION VALUES GENERALIZED
FROM FIELD-AIR PHOTO MAP TO MEAN
RATES FOR 10,000 SQ. FT. AREAS.

DATA VALUE EXTREMES ARE 0.0 3.60
INCHES OF WATER RETAINED

A
(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

	0.0	0.26	0.76	1.26	1.76	2.51	3.51
MINIMUM	0.0	0.26	0.76	1.26	1.76	2.51	3.51
MAXIMUM	0.26	0.76	1.26	1.76	2.51	3.51	3.60

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

	7.22	13.89	13.89	13.89	20.83	27.78	2.50
	7.22	13.89	13.89	13.89	20.83	27.78	2.50

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7
SYMBOLS	1	2	3	4	5	6	7
FREQ.	51	57	44	15	20	4	1

B
(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

	0.0	0.36	0.76	0.72	1.09	1.44	1.80	2.16	2.52	2.88	3.24
MINIMUM	0.0	0.36	0.76	0.72	1.09	1.44	1.80	2.16	2.52	2.88	3.24
MAXIMUM	0.36	0.76	0.72	1.09	1.44	1.80	2.16	2.52	2.88	3.24	3.60

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	56	52	29	18	12	12	8	3	0	2

C
(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

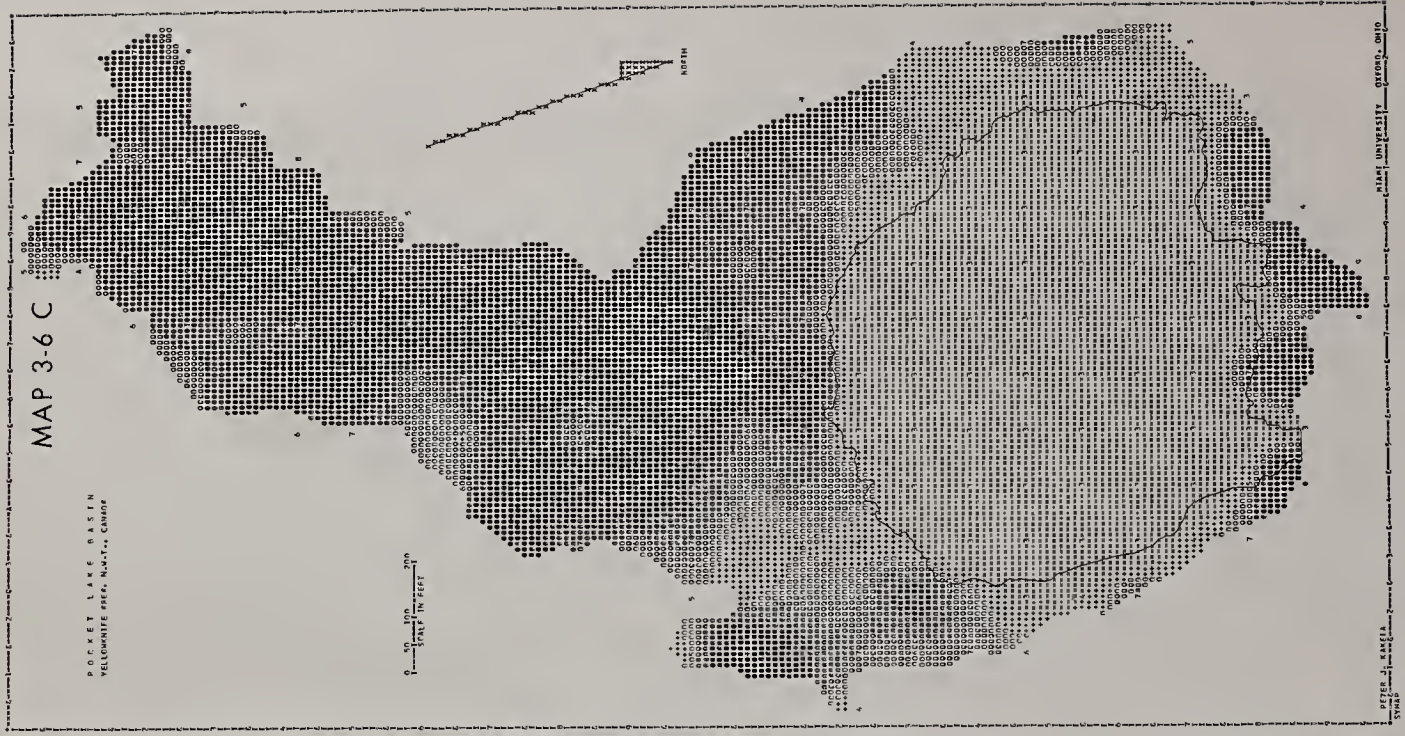
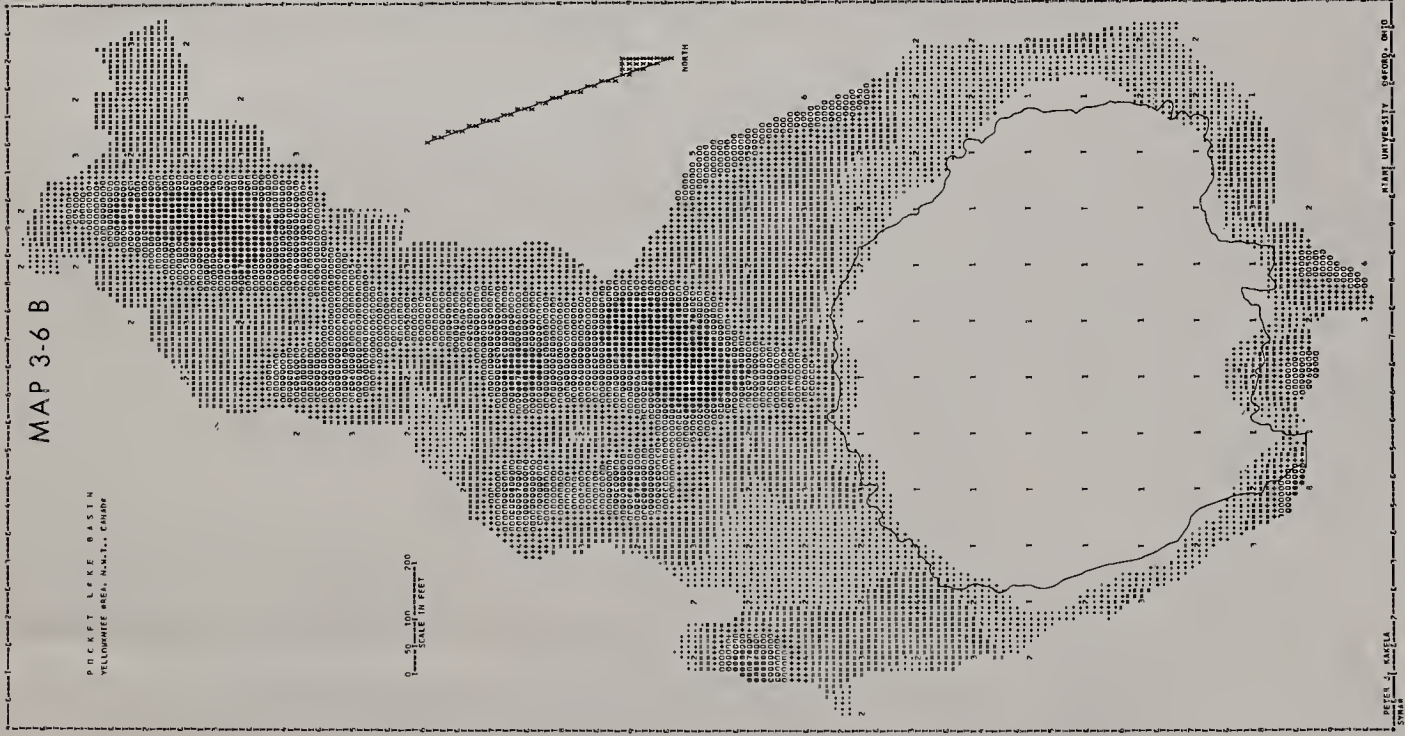
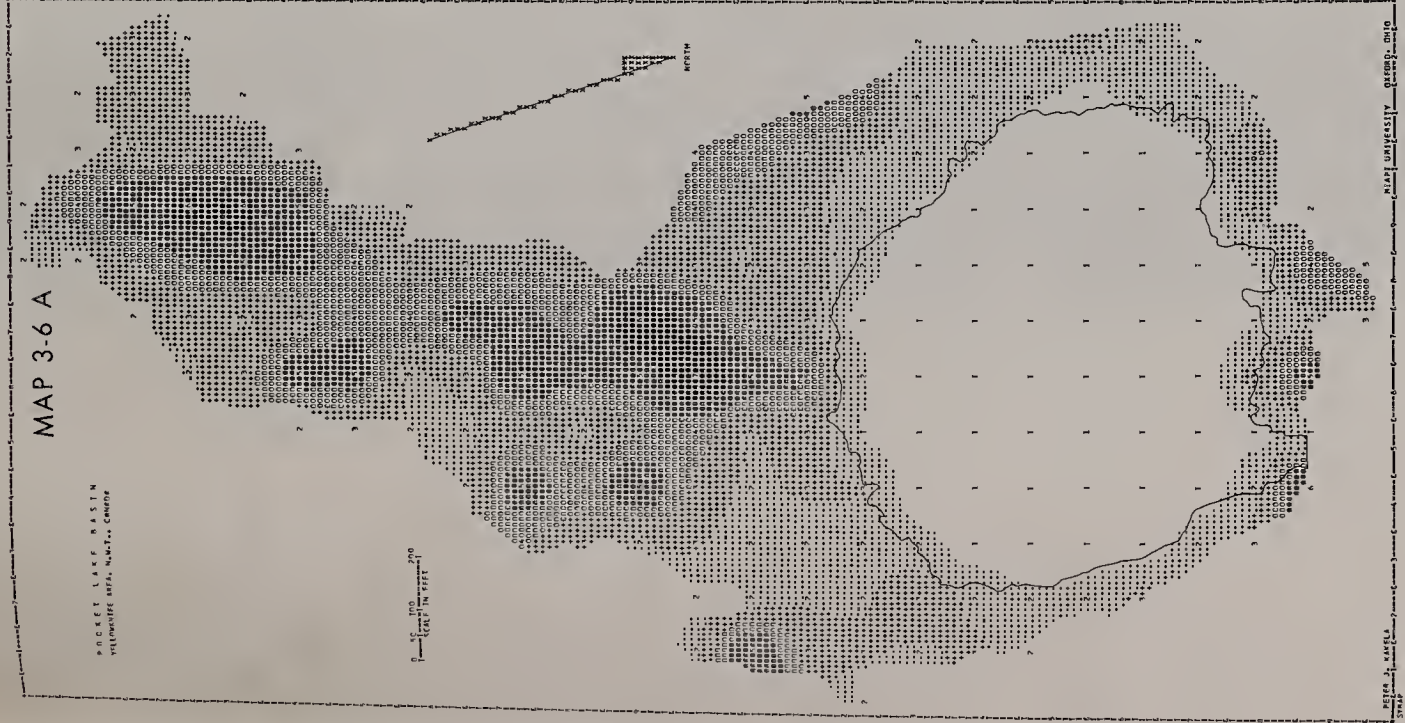
	0.0	0.0	0.0	0.40	0.60	0.70	0.80	1.00	1.31	2.00
MINIMUM	0.0	0.0	0.0	0.40	0.60	0.70	0.80	1.00	1.31	2.00
MAXIMUM	0.0	0.0	0.40	0.60	0.70	0.80	1.00	1.31	2.00	3.60

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

	0.0	0.0	11.11	5.56	2.78	2.78	5.56	8.61	19.17	44.44
	0.0	0.0	11.11	5.56	2.78	2.78	5.56	8.61	19.17	44.44

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	0	0	56	15	15	22	24	22	18	20



on the generalized map. The generalized map displays the same pattern of high retention in the several flat, moss covered depressions in the basin as does the detailed map. The low retention surfaces of the Lake itself and the bedrock knolls are distinguished by the lower classes. Map 3-6 A merely generalizes the retention pattern slightly, and also portrays it by means of the contour technique.

Map 3-6 B is a contour type map based on the same generalized retention data as Map 3-6 A; however, the data range (0.00 to 3.60 inches) is divided into ten classes, each containing 10 per cent of the range. The spatial patterns are very similar to Map 3-6 A, but showing slightly more gradation of gray tones through the higher classes because of the additional three classes. In both maps, the concentration of data points and mapped area is definitely toward the lower classes. The area weighted mean retention capacity of .81 of an inch was calculated from Map 3-6 B by a count of the printed characters per class.

For Map 3-6 C, the computer was programmed to divide the data into ten random classes, so that each class contained approximately 10 per cent of the data points. Since the data points used for these generalized maps have been assigned to the centers of the uniform grid squares, they are located at constant intervals. This means that 10 per cent of the data points will dominate approximately 10 per cent of the mapped area. These random class intervals were used to spread the data out from the low value concentration.

In Map 3-6 C the first two classes did not materialize because of the high frequency of 0.00 inch retention values. In effect, the first three classes were compounded as one and it was printed on the map as class three. Class three then, covers approximately 30 per cent of the mapped area. This class dominates the Lake surface and its surrounding bedrock slopes. The map also depicts the relatively high retention values of most of the rest of the drainage basin.

Generalized Surplus SYMAPs. If the values of spring surface retention for each generalized grid unit (192 values) are subtracted from the values of spring water equivalent for the respective unit, the result is the amount of surplus or lack of storage replenishment that occurs in that unit during spring 1967. Surplus water occurs when the depth of the snow water equivalent is greater than the spring retention capacity; lack of complete replenishment of spring storage occurs when the capacity to retain water is greater than the spring water accumulation for any unit area. These values will be expressed as the mean rates in inches of depth over the ground surface of the unit area. Values derived in this manner for the generalized units have been mapped in the Map 3-7 series.

Map 3-7 A is a contour map based on even inch class intervals which originate from zero and extend to the extremes of the range. The first class starts from zero and extends down to the lowest value of -.60 inches. This class includes all of the values that resulted in minus values when

Legend for Map 3-7
GENERALIZED SURPLUS, SPRING 1967

SURPLUS CALCULATED BY DEDUCTING SURFACE RETENTION
VALUES FROM SPRING SNOW COVER VALUES; BOTH
FACTORS GENERALIZED TO 10,000 SQ. FT. AREAS.

DATA VALUE EXTREMES ARE -0.60 4.80
EXPRESSED AS DEPTH IN INCHES OF RUNOFF

A
(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	-0.60	0.0	1.01	2.01	3.01	4.01
MAXIMUM	0.0	1.01	2.01	3.01	4.01	4.80

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

11.11	18.70	18.52	18.52	18.52	14.63
-------	-------	-------	-------	-------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6
SYMBOLS	1	2	3	4	5	6
FREQ.	3	11	44	94	37	3

B
(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	-0.60	-0.06	0.48	1.02	1.56	2.10	2.64	3.18	3.72	4.26
MAXIMUM	-0.06	0.48	1.02	1.56	2.10	2.64	3.18	3.72	4.26	4.80

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	3	5	6	17	27	50	50	74	8	2

C
(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

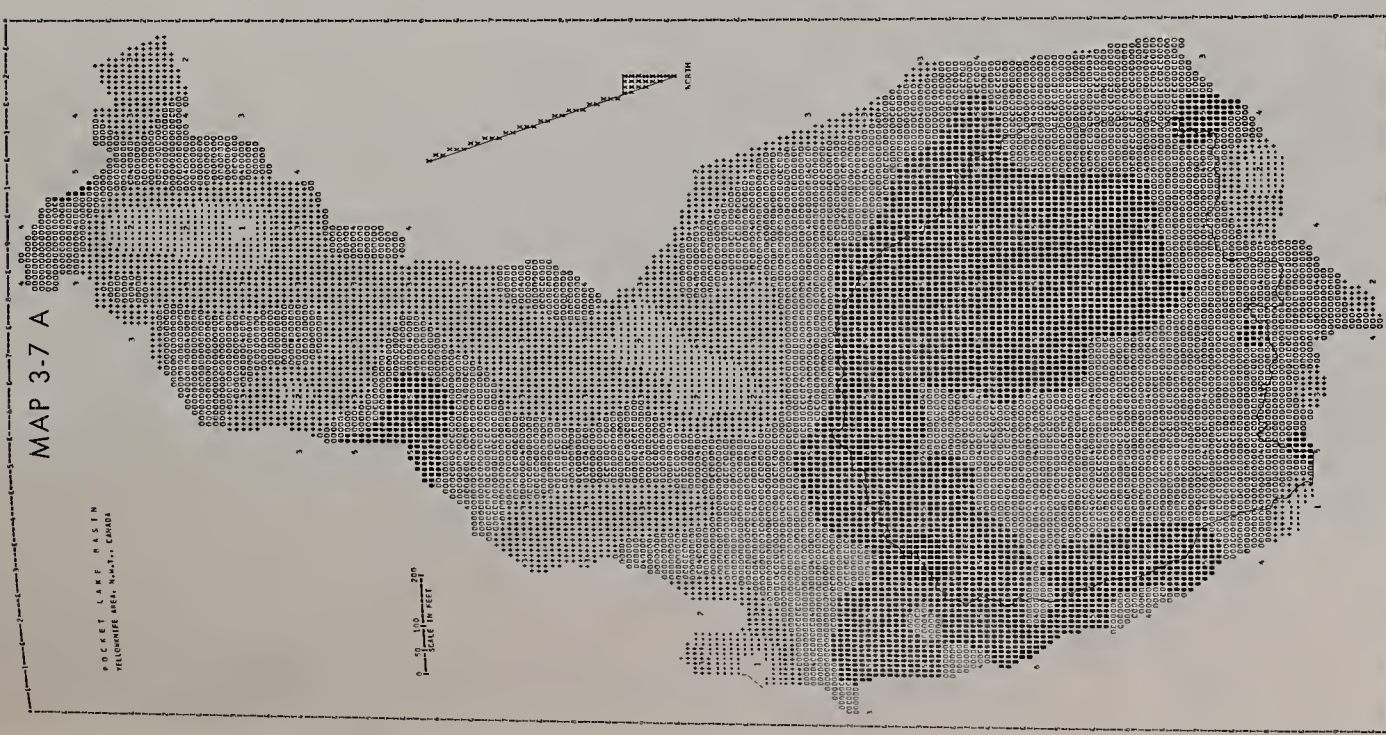
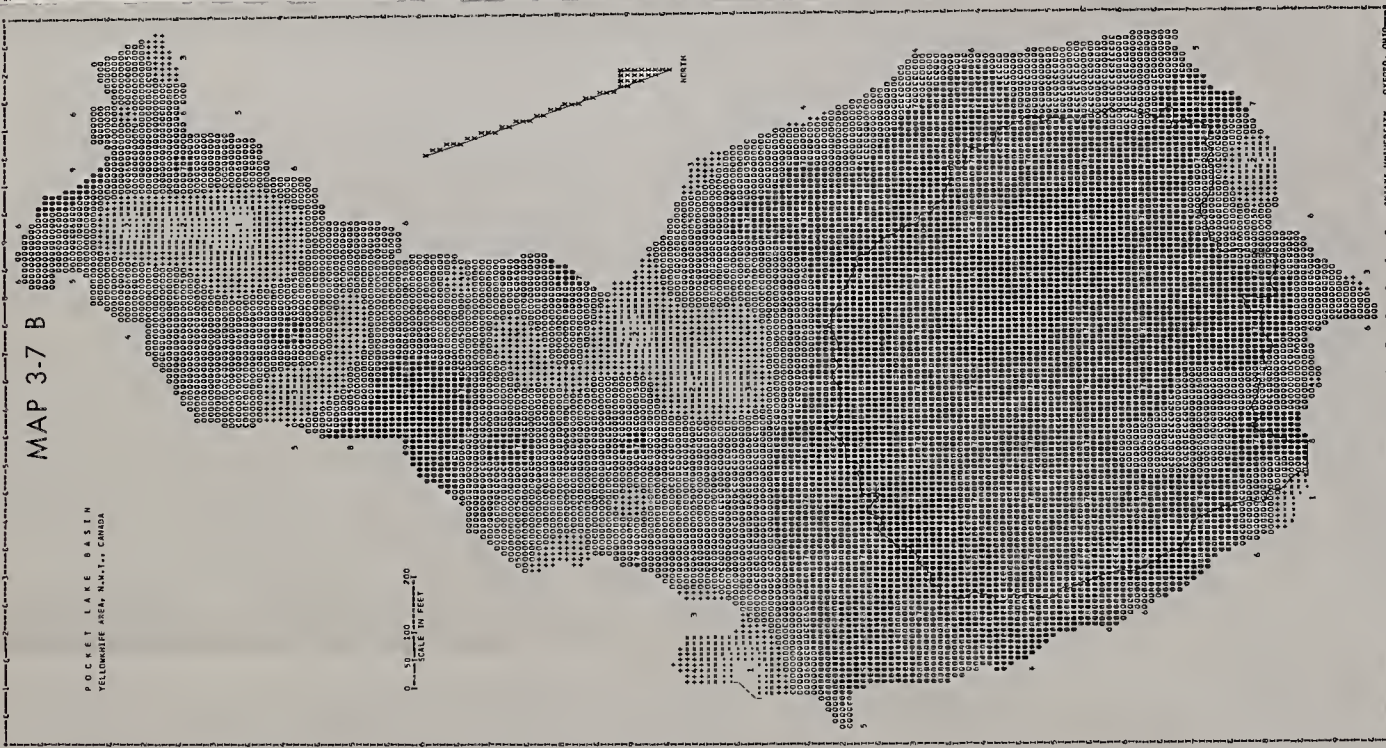
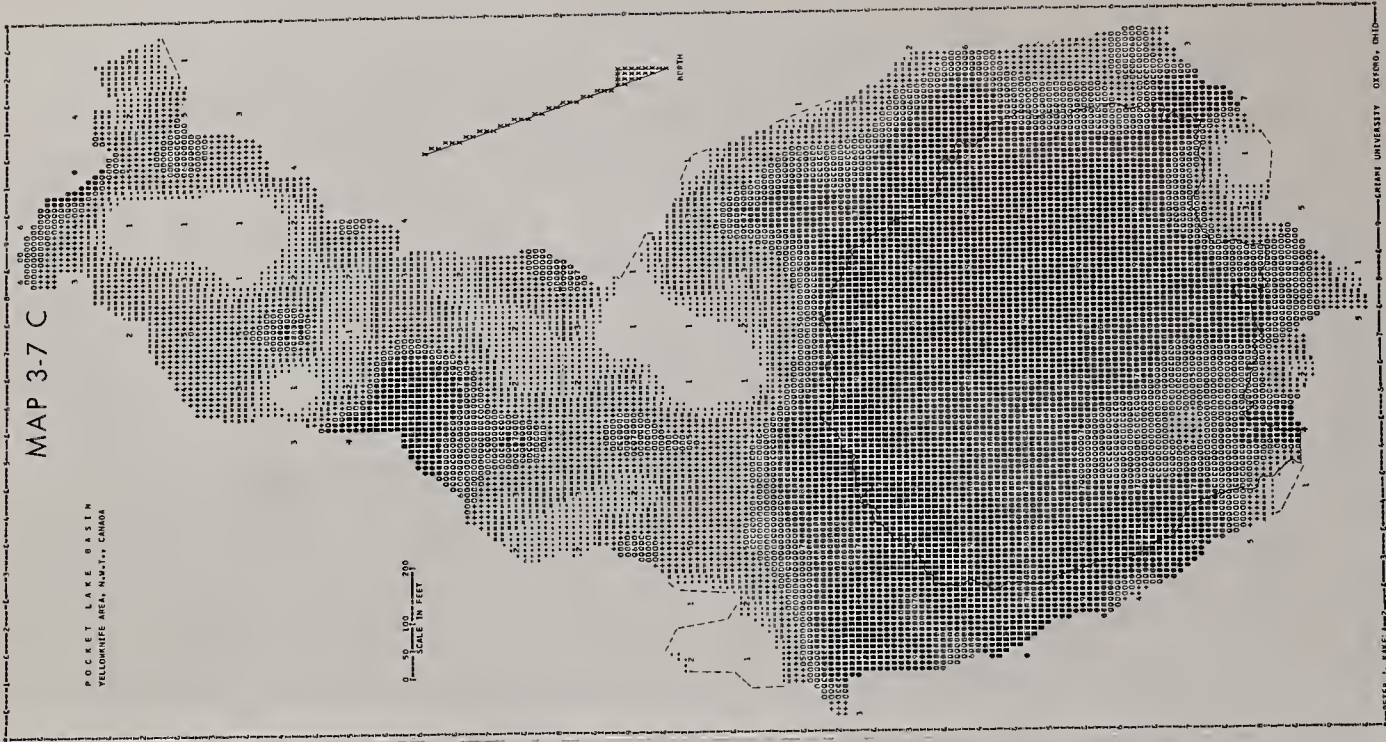
MINIMUM	-0.60	1.27	1.70	2.01	2.40	2.60	2.80	3.00	3.10	3.50
MAXIMUM	1.27	1.70	2.01	2.40	2.60	2.80	3.00	3.10	3.50	4.80

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

34.63	7.96	5.74	7.22	3.70	3.70	3.70	1.85	7.41	24.07
-------	------	------	------	------	------	------	------	------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	19	18	21	17	18	21	19	19	20	20



surface retention was subtracted from spring snow detention. It therefore depicts the areas in Pocket Lake basin that did not detain enough snow through the winter to completely recharge the 1967 spring retention of meltwater. The rest of the classes of Map 3-7 A represent different rates of surplus that were generated from the different segments of Pocket Lake basin in the spring of 1967.

The spatial pattern of generated surplus within the basin is interesting. It shows that the Lake surface, and especially the southern shore zone, is a large contributor of surplus. The main reason for this is that surplus was assumed to be that excess water which would be added to the Lake; certainly the lake ice and adjacent sloping bedrock surfaces presented little or no retention of spring meltwater. Within this high surplus generating zone there are two areas that contribute exceptionally large quantities of runoff, primarily because of greater snow detention than the adjacent surfaces. There are a few other areas throughout the basin which generate high rates of runoff, mainly because of low retention values and moderately high snow detention rates.

The high retention surfaces of the flat, moss covered depressions are manifested as areas generating small amounts of surplus. In fact, all three data points that were calculated to have negative surplus values were located in such flat, moss covered areas.

Map 3-7 B is a contour map based on the same derived spring surplus data as the previous map, but the data range

has been subdivided into ten classes of equal intervals. This map offers a more refined portrayal of the patterns of generated surplus because of the greater number of classes. It also shows that the data are skewed toward the higher surplus values. The Lake and shore areas are definitely within these higher values. Again, the low surplus generating areas are distinct, but there are extensive areas throughout the basin contributing greater than mean surplus.

In Map 3-7 C, the data points were divided so that approximately the same frequency was included in each of ten random interval classes. This means that the mapped area allotted to each class is also nearly equal (about 10 per cent) because of the uniform spacing of the generalized data points. The map illustrates the relative distribution of spring surplus for 1967. Map 3-7 C spatially emphasizes the contributing areas of relatively low surplus values. It also presents a more detailed distribution of the middle and high value surplus generating areas than either of the two previous maps.

Generalized Water Balance Relationships. The relationship of each generalized water balance component to the others was measured by correlating the three sets of values that were determined for the grid squares. From these correlations it is interesting to note the indicated relationships.

The correlation coefficient of water surplus to surface retention capacity was highest and negative

(-.725),³⁰ indicating that there was a tendency for the larger rates of surplus water to be generated from low retention surfaces. The correlation of maximum water equivalents detained in spring to surpluses was slightly less (.583), but indicates that there is a positive relation between higher snow accumulations and high spring surpluses. The correlation between snow water equivalents detained and spring surface retention capacities was quite low (.127) and not statistically significant, indicating the lack of a relationship between these components.

To illustrate the integration of the water balance components as derived from the refined areal units, formula 1.1 is again used. However, because the spring retention capacity is not completely filled with meltwater on all surfaces, an additional factor is necessary in the formula. The water balance for the more refined areal units is

$$Ppt = (PE - D) + Sur \pm SC - [ISR] , \quad (3.1)$$

where: ISR = incomplete storage recharge;
and other factors are as indicated previously.

The incomplete storage recharge occurs on certain surfaces which do not detain as much snow water equivalent in winter as they can retain once the snow is converted to water. Therefore, some surfaces can have incomplete retention storage recharge even though most other surfaces have spring

³⁰With 190 degrees of freedom (N-2), the correlation coefficient for the 1 per cent level of statistical significance is .185; for the 5 per cent level it is .142.

water surpluses. In considering the water balance on a basin-wide scale, the mean snow water equivalent was much greater than the spring retention capacity which implies ample spring moisture for full surface retention recharge plus considerable surplus.

With the smaller surface units, this was not found to be true. Using formula 3.1 and the water balance values determined through generalizing the detailed field maps to the uniform grid units, the 1967 spring water balance for Pocket Lake basin is

$$3.32 = (0 - 0) + 2.51 + .81 - [T],$$

where: T = trace.

The slightly higher precipitation and slightly lower addition to storage values are merely the result of recalculating and reapportioning these values according to the generalized grid squares. The higher surplus value is a compounded result of the two other deviant values because it is derived from them.

The important difference between these values and those calculated from the basin-wide means is the occurrence of any (a trace) incomplete storage recharge. The influence of this value is to cause a comparable, but inverse, change in the surplus value. That is, incomplete storage recharge occurs when: 1) the mean spring moisture exceeds the mean retention capacity, but 2) it does not actually recharge all of the potential retention because of the uneven distribution. Therefore, there must be a compensating amount of moisture located on another surface (with complete storage recharge) equal to the

amount of incomplete storage recharge. This relocated amount of moisture is equal in quantity to the incomplete recharge and is manifested as surplus.

An example may help to explain the relationship more fully. In considering the spring water balance over two adjacent grid units, assume a mean of four inches of snow water equivalent has collected through the winter and that each surface has a one inch water retention capacity. (See Figure 3-6 A for a schematic presentation.) If the snow precipitation is evenly distributed over both surfaces, then the complete retention capacity would be recharged and a mean depth of three inches of surplus would be generated from the surfaces. If the snow was very unevenly distributed, the spring water balance values would be different. As an extreme, if all of the snow was concentrated on one of the grid units (eight inches in depth) and the other was bare, the mean rate of: 1) incomplete storage recharge would equal one-half inch, 2) storage recharge would equal one-half inch, and 3) surplus would equal three and one-half inches of water. Thus, the surplus is increased by the amount of potential storage recharge that was not supplied.

Detailed Water Balance Relationships. In developing the snow detention and spring retention relationships, a greater refinement of areal units was also employed. Map 3-7 D is a composite of the Field Map of snow water equivalents (Map 3-1) and the field estimated Surface Retention Map

SCHEMATIC PRESENTATION OF SPRING WATER BALANCE RELATIONSHIPS

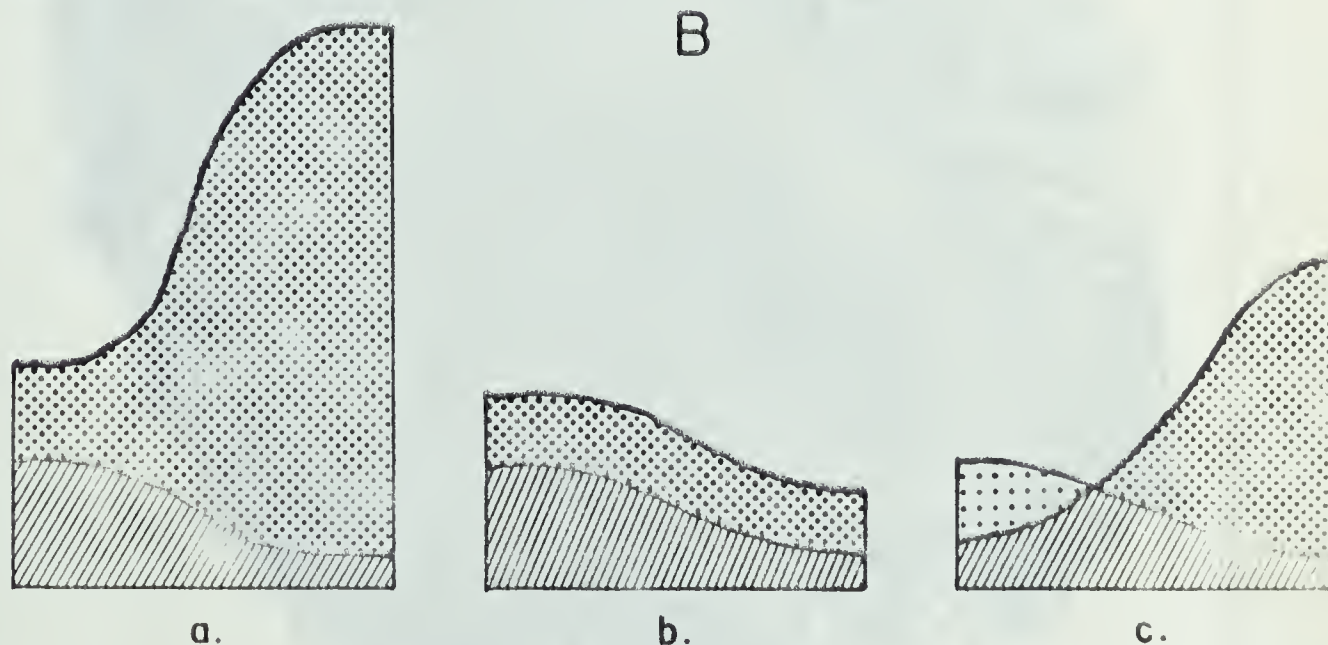
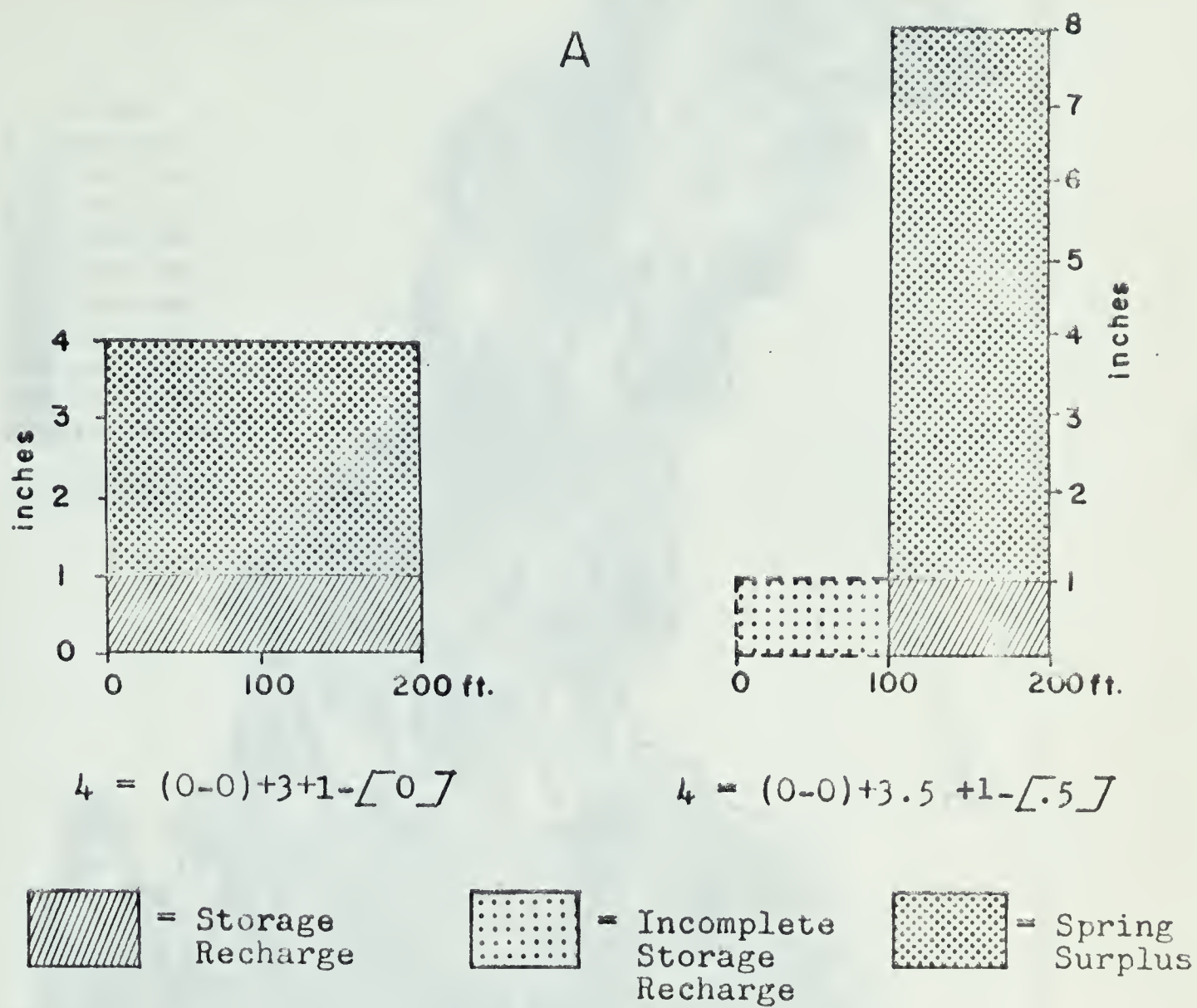
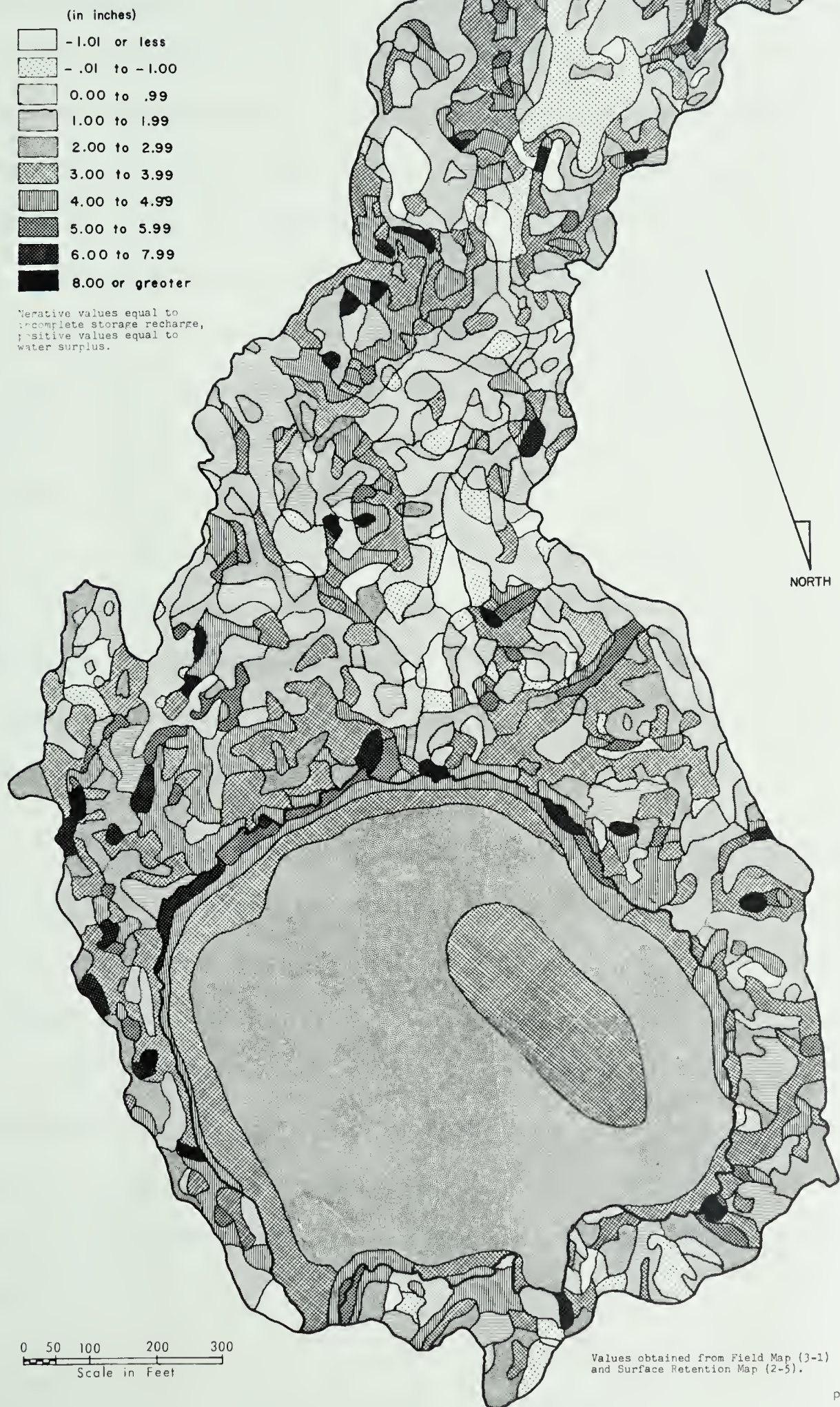


Figure 3-6

Map 3-7 D

DETAILED WATER SURPLUS AND INCOMPLETE STORAGE RECHARGE, SPRING 1967

POCKET LAKE BASIN
Yellowknife Aeo, N.W.T., Canada



(Map. 2-5). Boundaries that occurred on either map were used to delimit the areal units. For each delimited area, the surface retention value was subtracted from the snow detention value to yield a measure of resulting surplus or incomplete storage recharge. Thus, a spring water balance was calculated for each map unit. The area of each unit was determined in the same manner as was explained for the two field maps, and mean values for the entire basin were calculated.

Accentuation of the water balance values resulted from the use of the more refined areal units. Based on area weighted values calculated from Map 3-7 D and using formula 3.1, the 1967 spring water balance is:

$$3.23 = (0 - 0) + 2.50 + .78 - [.05]$$

On the basis of the more refined areal units a larger incomplete storage recharge, and thus a smaller spring storage recharge, was calculated for the basin. The derived water surplus is increased accordingly.

Conclusion. It can be concluded that the refinement of the areal unit for which the water balance is calculated tends to indicate more detail about the source areas of the variables and also refines mean basin values for these variables. The consideration of smaller areas allows the identification of surfaces which do not have complete storage recharge in spring. It also allows more detailed interpretation of the effects of uneven snow distribution on surpluses generated.

The writer believes that the amount of areal refinement of spring water balance components is directly related to the intensity of snow drifting and inversely related to the quantity of snow accumulation. That is, if the drifting is very severe, but there is a large snow accumulation, small unit areas will not refine the water balance relationships because there will always be ample moisture to fill storage and supply surplus from all surfaces. (See Figure 3-6 B.) If there is a limited snow cover that has drifted so that it is distributed proportionately to the retention capacities of the surfaces, there would still be complete recharge and some surplus from all surfaces. In both of these cases a refined areal unit would yield no more information than considering basin-wide mean values.

If the drifting is severe and the resulting snow cover is not proportionate to the surface retention distribution, then some surfaces may have incomplete storage recharge. With areal refinement these surfaces can be delimited and other spring water balance variables can be adjusted accordingly. Thus, refinement of the areal scale is important when there is limited snow accumulation and significant drifting.

Based upon the snow accumulation and surplus generation relationships developed here, a number of water balance equations are presented in chapter IV. The values for these equations express seasonal and land surface variations of water balance components in the Yellowknife Area. Discussion

of other snow cover aspects observed in Pocket Lake basin comprise the latter portion of the present chapter.

1967 Snow Depths in Pocket Lake Basin

Introduction

The distribution of the depth of snow cover in the Pocket Lake basin is another aspect of snow precipitation in the area. Snow depth influences environmental factors, such as the thermal properties of the ground, because of the insulating effect of a snow cover. Also, the depth of snow is another measure of snow drifting. Thus, it was felt that the mapping of the 1967 snow depth measurements for Pocket Lake basin was a valuable addition to the analysis of snow precipitation. No attempt was made to extend the sample measurements through field estimations of the areal application of each sample. Therefore, the collected data were punched on cards and maps were planned for use in the SYMAP program. The resulting maps illustrate some interesting factors of the distribution and change of snow depth.

April Measurements

The Map 3-8 series of snow depth maps is based on the ninety-six sample values obtained in April, 1967. Map 3-8 A is a contour map with ten classes. The first nine of these classes are based on equal intervals and the class boundaries are identical for the A and B maps in all three series of

Legend for Map 3-8

SNOW DEPTH, APRIL 28-29, 1967

MOUNT ROSE TYPE SNOW SAMPLED USED
BY LARRY STEF AND PETER KAKELA.

DATA VALUE EXTREMES ARE

0.0 38.00
INCHESA
(Contour Type Map)ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.0	3.33	6.67	10.00	13.33	16.67	20.00	23.33	26.67	30.00	ABS. MAX.
MAXIMUM	3.33	6.67	10.00	13.33	16.67	20.00	23.33	26.67	30.00		38.00

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11
-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	2	6	3	2	11	18	35	11	6	2

B
(Proximal Type Map)ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.0	3.33	6.67	10.00	13.33	16.67	20.00	23.33	26.67	30.00	ABS. MAX.
MAXIMUM	3.33	6.67	10.00	13.33	16.67	20.00	23.33	26.67	30.00		38.00

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11
-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10	11
SYMBOLS	1	2	3	4	5	6	7	8	9	10	11
FREQ.	2	6	3	8	11	18	35	11	6	2	2

C
(Contour Type Map)ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.0	12.10	15.35	17.50	18.95	20.50	21.00	22.00	23.15	25.00	ABS. MAX.
MAXIMUM	12.10	15.35	17.50	18.95	20.50	21.00	22.00	23.15	25.00		38.00

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

31.84	8.55	5.66	3.82	4.09	1.32	2.63	3.03	4.87	24.21
-------	------	------	------	------	------	------	------	------	-------

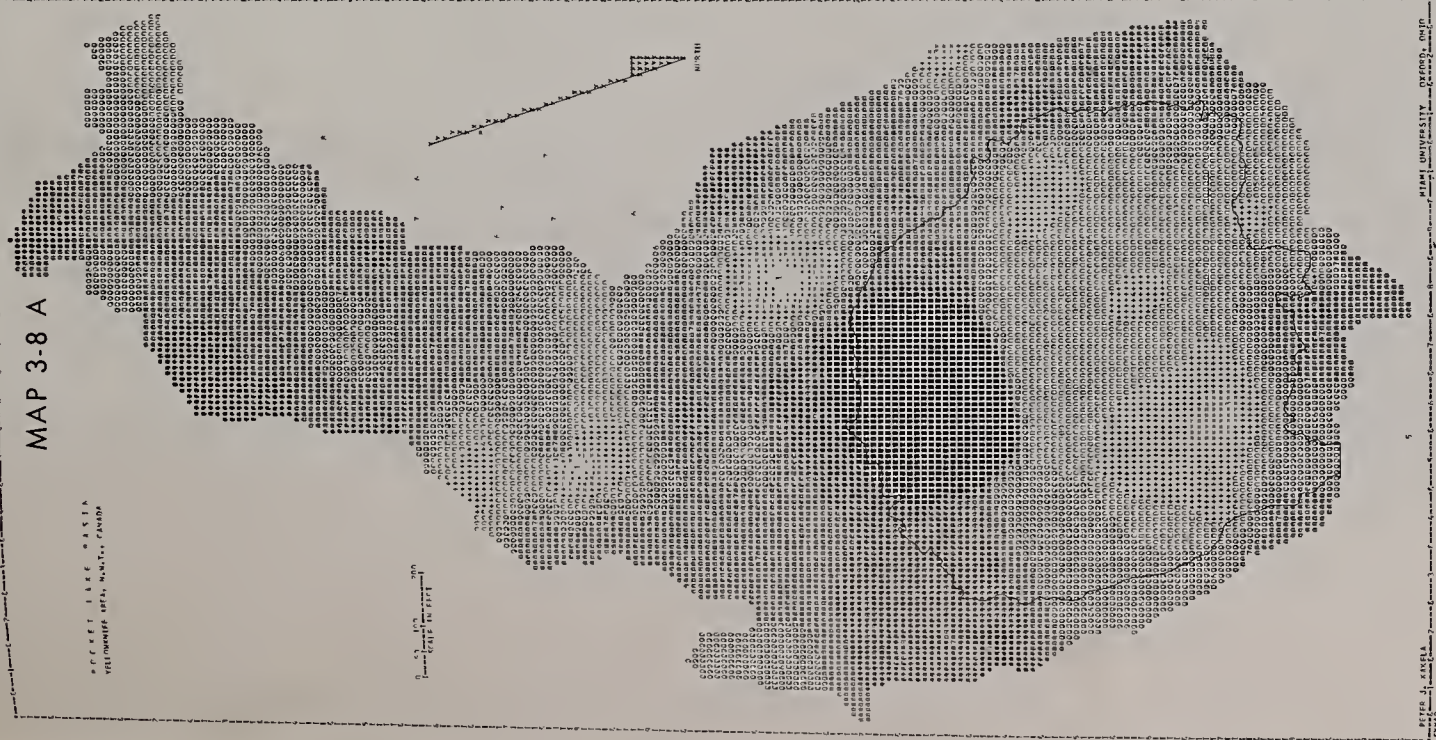
FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	10	9	9	10	9	3	16	11	0	11

MAP 3-8 A

POINT LANE BASIN
WILLIAMS BASIN, N.M., CANADA

0 1 2 3 4 5 6 7 8 9 10
MILES

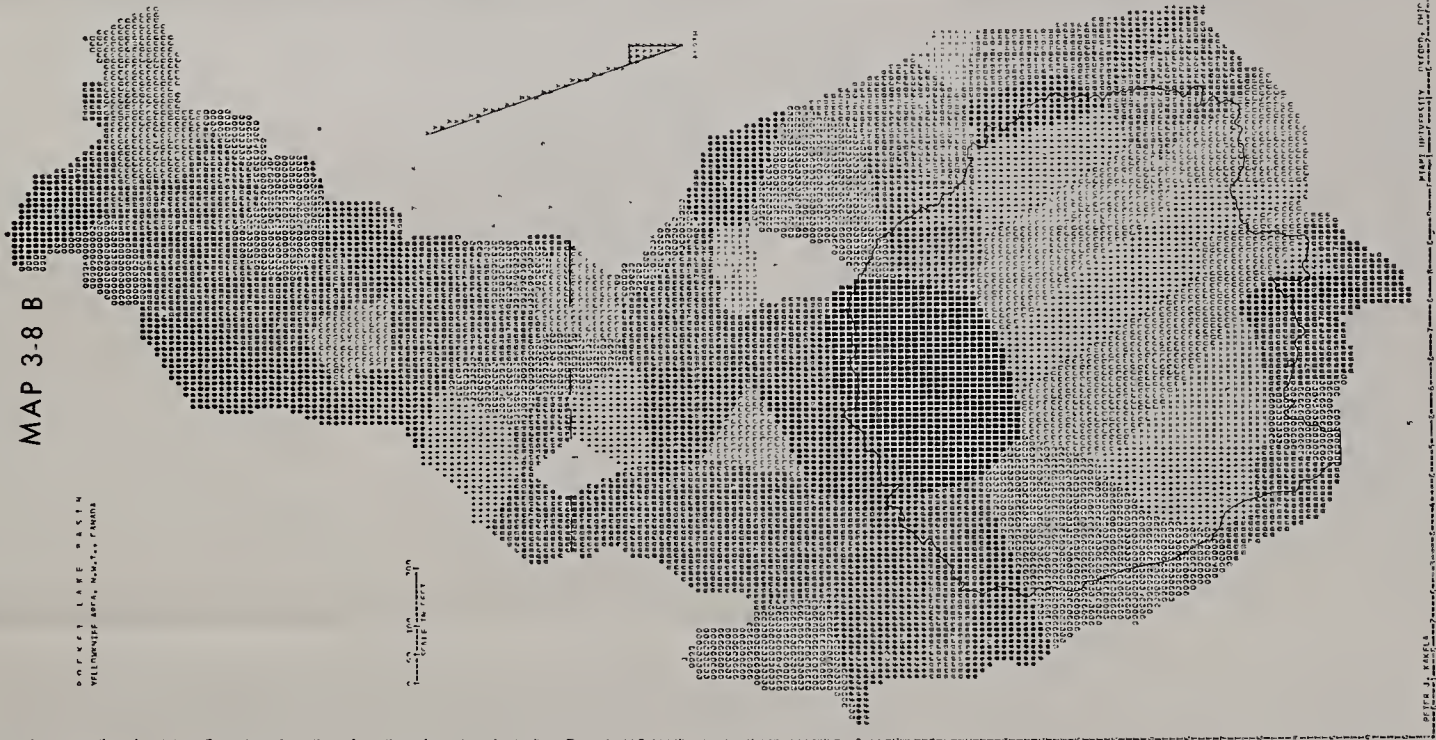


PETER J. KINLA
MIAMI UNIVERSITY, OXFORD, OHIO

MAP 3-8 B

POINT LANE BASIN
WILLIAMS BASIN, N.M., CANADA

0 1 2 3 4 5 6 7 8 9 10
MILES

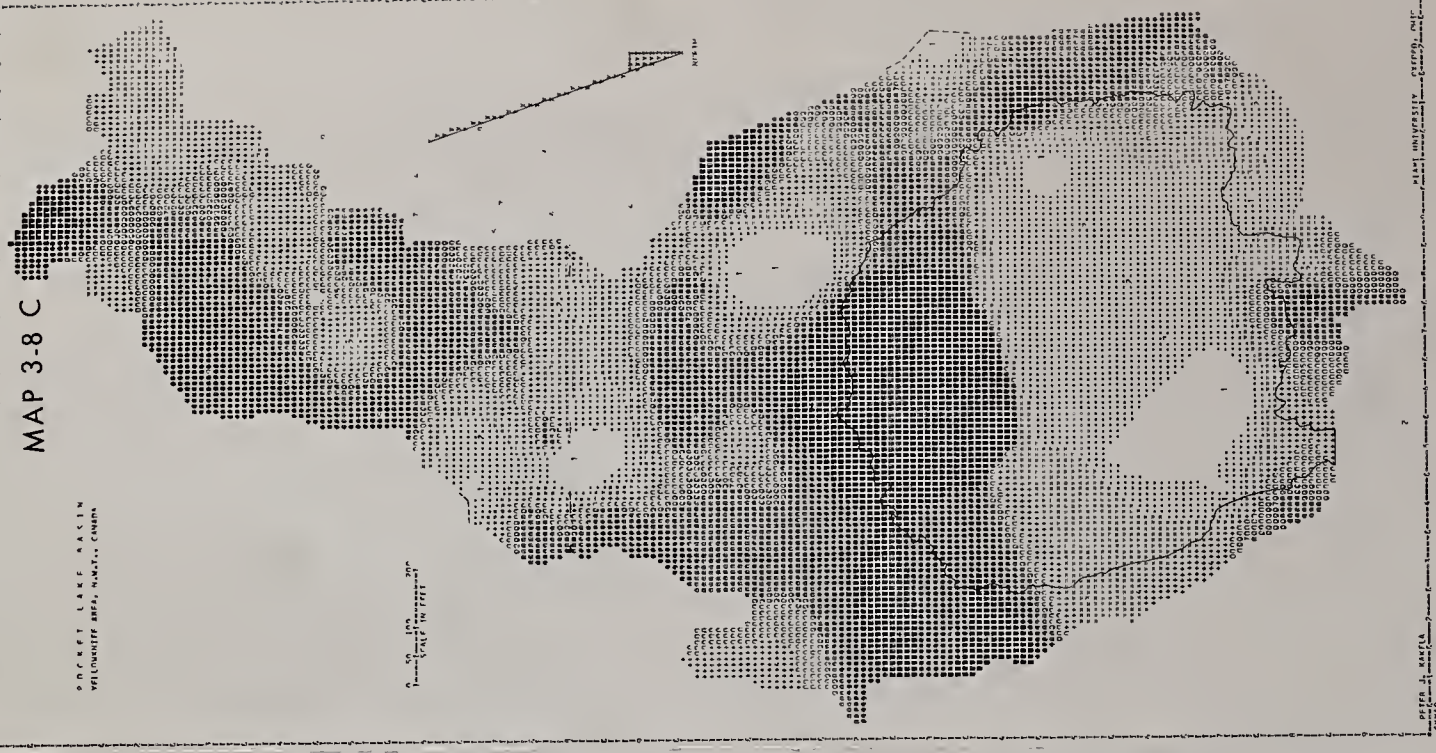


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MIAMI UNIVERSITY, OXFORD, OHIO

MAP 3-8 C

POINT LANE BASIN
WILLIAMS BASIN, N.M., CANADA

0 1 2 3 4 5 6 7 8 9 10
MILES



PETER J. KINLA
MIAMI UNIVERSITY, OXFORD, OHIO

maps to be presented on 1967 snow depth. This consistency of classes was maintained for the purpose of facilitating comparison among these six maps. The tenth class for all six maps begins at 30.00 inches, but has a maximum boundary according to the maximum values of the sampling period.

The frequency of data points in Map 3-8 A is skewed toward the deeper values with class seven being the modal class with boundaries of 20.00 to 23.32 inches of snow. The skewness toward the higher values is illustrated by the rather dark, general shading of the map itself. The circular area of class ten, with a maximum value of thirty-eight inches, located around the southern shore of Pocket Lake is extended too far onto the Lake surface. However, much of the central area of the Lake is depicted properly as being in the lower snow depth classes.

The proximal Map 3-8 B is printed according to the identical class limits and data as the preceding map. It shows slightly more contrast and is slightly lighter in overall tone than the contour map even though the frequency distribution is the same.

Map 3-8 C is a contour map with a random progression of class intervals so that the data are spread out with approximately the same number of data points in each class. This map illustrates the relatively small snow depths over the central portion of the Lake and some bedrock knolls in the basin. The deeper snow covers are concentrated along the south and southeast shore of the Lake and in some scattered

pockets throughout the basin. There is a high degree of visual correlation between the respective maps of the Map 3-8 series and those of the Map 3-2 series of April water equivalents.

May Measurements

The 279 May, 1967, snow depth measurements are portrayed in the Map 3-9 series. Map 3-9 A is a contour map with the previously mentioned constant class intervals except for the accommodation of the extreme values in the tenth class. The frequency of data points is concentrated in the mid-classes of four through seven, i.e., 10.00 inches through 23.32 inches of snow depth. This is a definite shift of frequency toward the lower snow depths for May as compared to the April measurements; Map 3-9 A illustrates this by the dominance of light gray tones compared to Map 3-8 A.

It is interesting that the maximum May snow depth (thirty-five inches) is lower than the April maximum (thirty-eight inches); however, there was a slightly greater proportion of class ten snow depth values measured in May than April. The writer interprets these changes in depth as indicating: 1) some surficial melting of the snow between the April and May measurements thus causing the generally smaller snow depth values of May, and 2) that a greater proportion of drifted pockets were located and sampled in May than in April, partly because they were slightly more obvious after some limited surficial melting occurred.

Legend for Map 3-9
SNOW DEPTH, MAY 9-11, 1967

MOUNT ROSE TYPE SNOW SAMPLES USED
BY LARRY STONE AND PETER KAKELA.

DATA VALUE EXTREMES ARE

0.0 35.00
INCHES

A
(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.0	3.33	6.67	10.00	13.33	16.67	20.00	23.33	26.67	30.00	ABOVE 30.00
MAXIMUM	3.33	6.67	10.00	13.33	16.67	20.00	23.33	26.67	30.00		

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	
-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	--

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10	11
SYMBOLS	1	2	3	4	5	6	7	8	9	10	11
FREQ.	2	4	17	64	44	64	47	16	12	8	

B
(Proximal Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.0	3.33	6.67	10.00	13.33	16.67	20.00	23.33	26.67	30.00	ABOVE 30.00
MAXIMUM	3.33	6.67	10.00	13.33	16.67	20.00	23.33	26.67	30.00		

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	
-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	--

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10	11
SYMBOLS	1	2	3	4	5	6	7	8	9	10	11
FREQ.	2	4	17	64	44	64	47	16	12	8	

C
(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

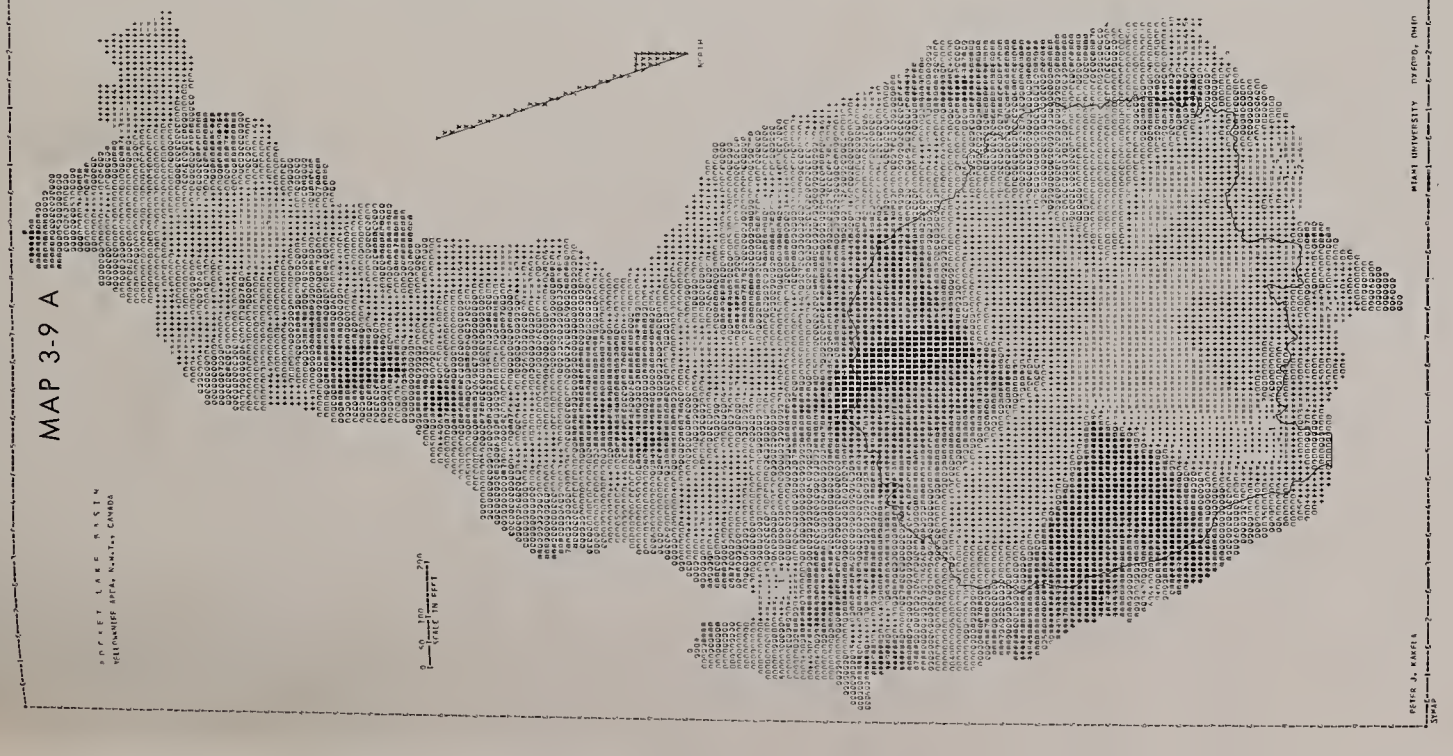
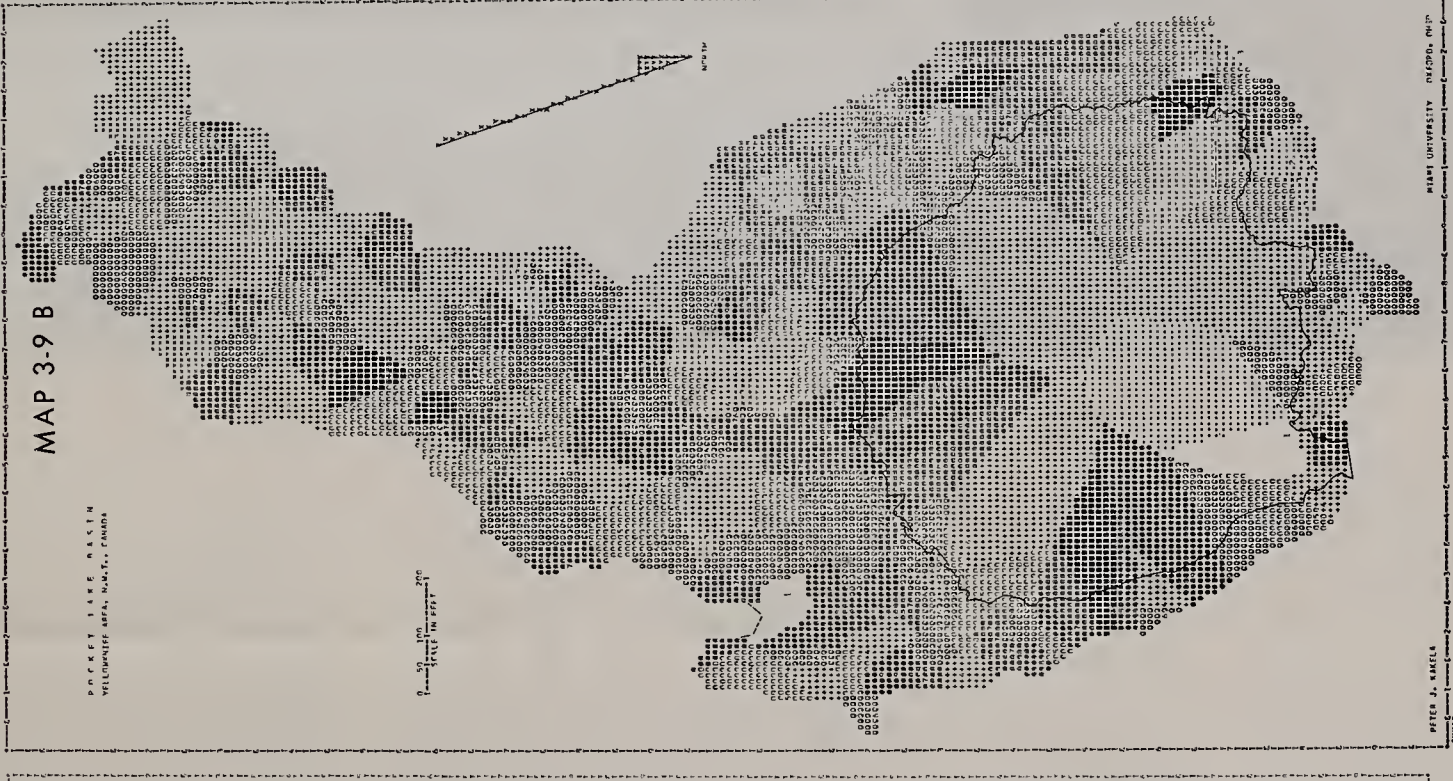
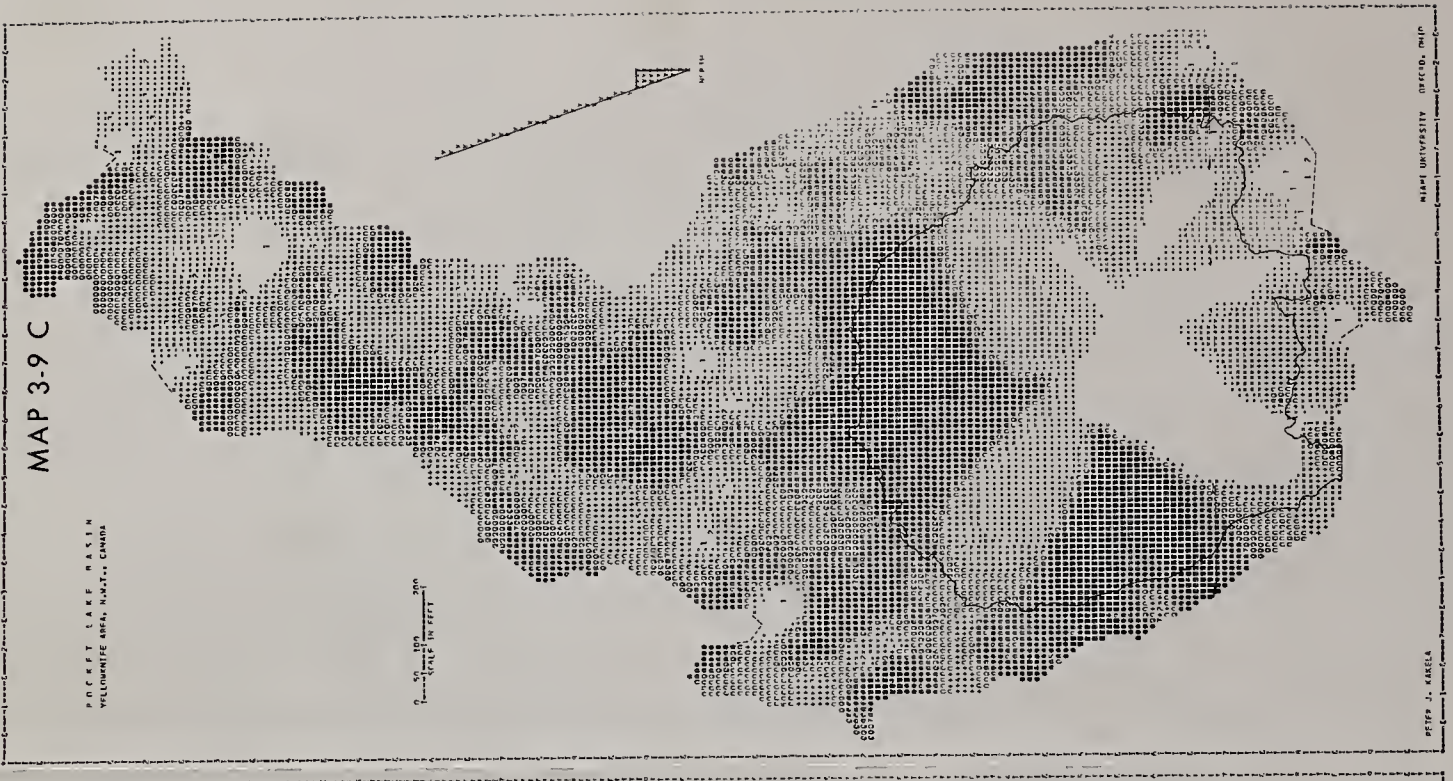
MINIMUM	0.0	10.00	11.00	13.00	15.00	17.00	18.00	19.00	21.00	25.00	35.00
MAXIMUM	10.00	11.00	13.00	15.00	17.00	18.00	19.00	21.00	25.00		

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

28.57	2.86	5.71	5.71	5.71	2.86	5.14	3.43	11.43	20.57	
-------	------	------	------	------	------	------	------	-------	-------	--

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10	11
SYMBOLS	1	2	3	4	5	6	7	8	9	10	11
FREQ.	23	19	36	25	20	26	33	12	41	31	



The proximal Map 3-9 B is the discontinuous presentation of the May snow depths. The map has a more complex pattern than the Map 3-8 series because it is based on more numerous data point values. This suggests that, along with water equivalent patterns, snow depths are also very heterogeneous within the small area of the Pocket Lake basin where the total winter snow accumulation is low and drifting is marked.

There appears to be less of a visual correlation between the May snow depth maps and the May water equivalent maps than was the case for the April maps. This suggests that the water equivalent of the snowpack is more closely related to snow depth before any melt has occurred than after surficial melting begins. Thus, for a given time interval in spring, the rate of surficial melting can vary in amount for different locations within the basin. For example, the deep snow area sampled on the south shore of the Lake (i.e., north facing and sloping) contained only a moderate amount of water equivalent (see Map 3-3 A, B, or C); whereas, the deep snow area situated on the uplands above the east shore contained a high quantity of water equivalent. This differential melting pattern within the basin requires more specific research before accurate relationships can be drawn.

Map 3-9 C is the random class interval map employing contour lines. The class boundaries were established so that the values would be spread out into classes with a more consistent frequency than occurred with the constant interval

classes. The two deep snow areas just discussed are even more prominent. Several smaller pockets of deep snow scattered in the basin are apparent. The central and north portions of the Lake are indicated as having quite low snow depths. Two of the flat, marshy depressions are also shown as having shallow snow accumulation.

Combined April and May Measurements

All of the 375 sample values of snow depth obtained in the spring of 1967 were used as input for the Map 3-10 series. The contour Map 3-10 A is based on the nine constant class intervals, with the tenth class expanded to cover the extremes. The high frequency of data point values is definitely concentrated in the middle classes including depth from 10.00 through 23.32 inches of snow. The general tone of the map is closer to "middle gray" than similar maps for April or May.

Map 3-10 B is the proximal type map displaying the same data as the previous map. The deep snow area on the south shore of the Lake is very pronounced. The depiction of this area is erroneous in its extension onto the Lake surface, but the shore portion is more nearly accurate. The shore area is steeply sloping with some vegetation covering this part of the main drainage channel leading into the Lake.

Map 3-10 C is the contour map based on randomly apportioned class intervals, selected so that the data are distributed rather evenly throughout the classes. The map has

Legend for Map 3-10

SNOW DEPTH, APRIL 28-29 and MAY 9-11, 1967

MOUNT ROSE TYPE SNOW SAMPLER USED BY TARRY STENE AND PETER KAKELA. DATA VALUE EXTREMES ARE 0.0 38.00 INCHES

A
(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY										
MINIMUM	0.0	3.33	6.67	10.00	13.33	16.67	20.00	23.33	26.67	30.00
MAXIMUM	3.33	6.67	10.00	13.33	16.67	20.00	23.33	26.67	30.00	38.00
PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL										
	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	
FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL										
LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	4	4	20	72	56	82	82	27	10	10

B
(Proximal Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY										
MINIMUM	0.0	3.33	6.67	10.00	13.33	16.67	20.00	23.33	26.67	30.00
MAXIMUM	3.33	6.67	10.00	13.33	16.67	20.00	23.33	26.67	30.00	38.00
PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL										
	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	
FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL										
LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	4	4	20	72	56	82	82	27	10	10

C
(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY										
MINIMUM	0.0	10.00	12.00	14.00	16.00	17.50	19.00	21.00	22.00	25.00
MAXIMUM	10.00	12.00	14.00	16.00	17.50	19.00	21.00	22.00	25.00	35.00
PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL										
	26.32	5.26	5.26	5.26	3.95	3.95	5.26	2.63	7.89	34.21
FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL										
LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	20	36	37	38	46	30	42	36	42	42

MAP 3-10 C

POLYMER LASE MASSIN
YELLOWHOLE AREA, N.W.T., CANADA

Scale 1:50,000
1:50,000

MAP 3-10 C
POLYMER LASE MASSIN
YELLOWHOLE AREA, N.W.T., CANADA
1:50,000

MAP 3-10 B

POLYMER LASE MASSIN
YELLOWHOLE AREA, N.W.T., CANADA

Scale 1:50,000
1:50,000

MAP 3-10 B
POLYMER LASE MASSIN
YELLOWHOLE AREA, N.W.T., CANADA
1:50,000

MAP 3-10 A

POLYMER LASE MASSIN
YELLOWHOLE AREA, N.W.T., CANADA

Scale 1:50,000
1:50,000

MAP 3-10 A
POLYMER LASE MASSIN
YELLOWHOLE AREA, N.W.T., CANADA
1:50,000

strong contrast in tone which emphasizes the deep snow area of the south shore and the shallow snow covered Lake surface.

1967 Snow Specific Gravity in Pocket Lake Basin

Introduction

The depth of the snow cover is directly related to the water equivalent contained within the snow depth and vice versa; however, this relationship is not a constant proportion. The snow variable that expresses the proportion of water equivalent to snow depth is the specific gravity of the snow. In definition, it is the density of the snow expressed as a proportion of the density of water.

The specific gravity value of each snow sample in this study was derived by dividing the measured depth of snow into the measured water equivalent of the sample. The result was carried to three decimal places. Thus, if the snow depth for two samples was the same (e.g., twenty inches), but the water equivalents differed (e.g., four inches and six inches), the specific gravities of the samples would differ accordingly (i.e., .200 and .300 respectively). In other words, the first sample is in less dense snow than the second.

The specific gravity of snow can vary considerably for several reasons. At the time it is precipitated, new snow can vary in specific gravity. Some diverse examples would include light, powdery snow crystals, partially melted snow plates, ice needles or columns, and graupel. Once on the

ground, snow can be compressed as dry crystals, regelated, or increased in density by refreezing percolating meltwater. These processes are capable of changing the specific gravity of a snowpack..

April Measurements

The derived specific gravity values from the April 28-29, 1967, snow samples taken in Pocket Lake basin are mapped in the Map 3-11 series. The two samples that recorded zero water equivalent and snow depth were excluded because there was no snow, thus no specific gravity, at these sites. Therefore, the maps are based on ninety-four data point values. The class boundaries for the contour (Map 3-11 A) and proximal (Map 3-11 B) maps are identical and were developed on the basis of the total range of all the 1967 specific gravity values. The total 1967 range was used so that these maps could be compared in absolute value of specific gravity to subsequent maps of May data and maps of the combined April and May data. The total range was divided into ten equal interval classes.

The April specific gravity values occurred in only the first six of the classes developed on the full range of 1967 specific gravity measurements. Therefore, Map 3-11 A and Map 3-11 B are based on only six classes. Both maps subsequently have an overall light gray tone to them indicating the dominance of low values. Within the six classes represented, the highest frequency of data points occurs in the

Legend for Map 3-11

SPECIFIC GRAVITY, APRIL 28-29, 1967

MOUNT ROSE TYPE SNOW SAMPLER USED
BY LARRY STENE AND PETER KAKELA.

DATA VALUE EXTREMES ARE 0.13 0.35

TOTAL MISSING DATA POINTS 2

A
(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.13	0.17	0.20	0.24	0.28	0.31
MAXIMUM	0.17	0.20	0.24	0.28	0.31	0.35

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

16.82	17.29	17.29	16.82	17.29	14.49
-------	-------	-------	-------	-------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6
SYMBOLS	1	2	3	4	5	6
FREQ.	14	18	37	15	8	2

B
(Proximal Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.13	0.17	0.20	0.24	0.28	0.31
MAXIMUM	0.17	0.20	0.24	0.28	0.31	0.35

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

16.82	17.29	17.29	16.82	17.29	14.49
-------	-------	-------	-------	-------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6
SYMBOLS	1	2	3	4	5	6
FREQ.	14	18	37	15	8	2

C
(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.13	0.17	0.19	0.20	0.21	0.22	0.23	0.24	0.26	0.28
MAXIMUM	0.17	0.19	0.20	0.21	0.22	0.23	0.24	0.26	0.28	0.35

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

16.36	9.44	5.98	6.12	4.16	4.21	3.74	9.07	9.39	31.54
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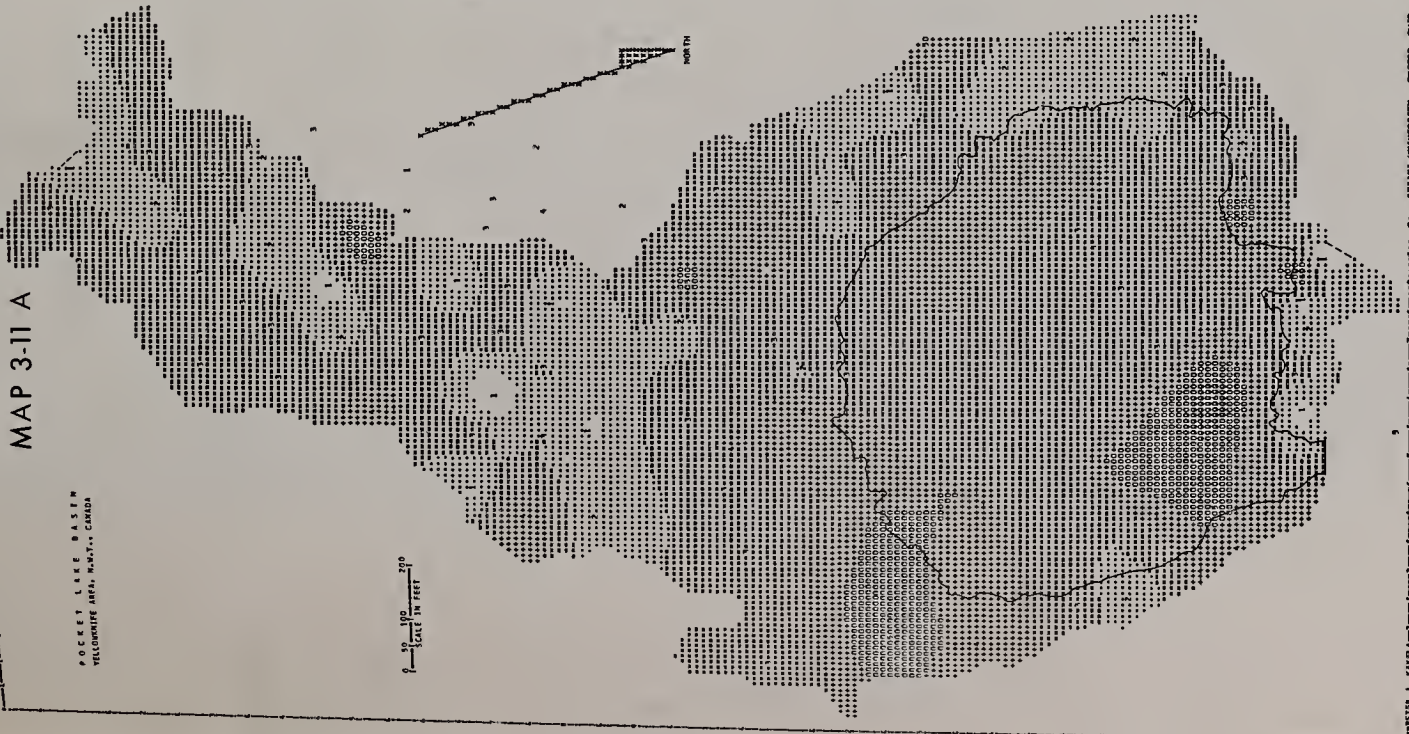
FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	4	15	8	11	8	9	10	10	10	9

MAP 3-II A

POCKET LAKE BASIN
YELLOWHIVE AREA, N.W. 1/4, CANADA

0 10 20
SCALE IN FEET

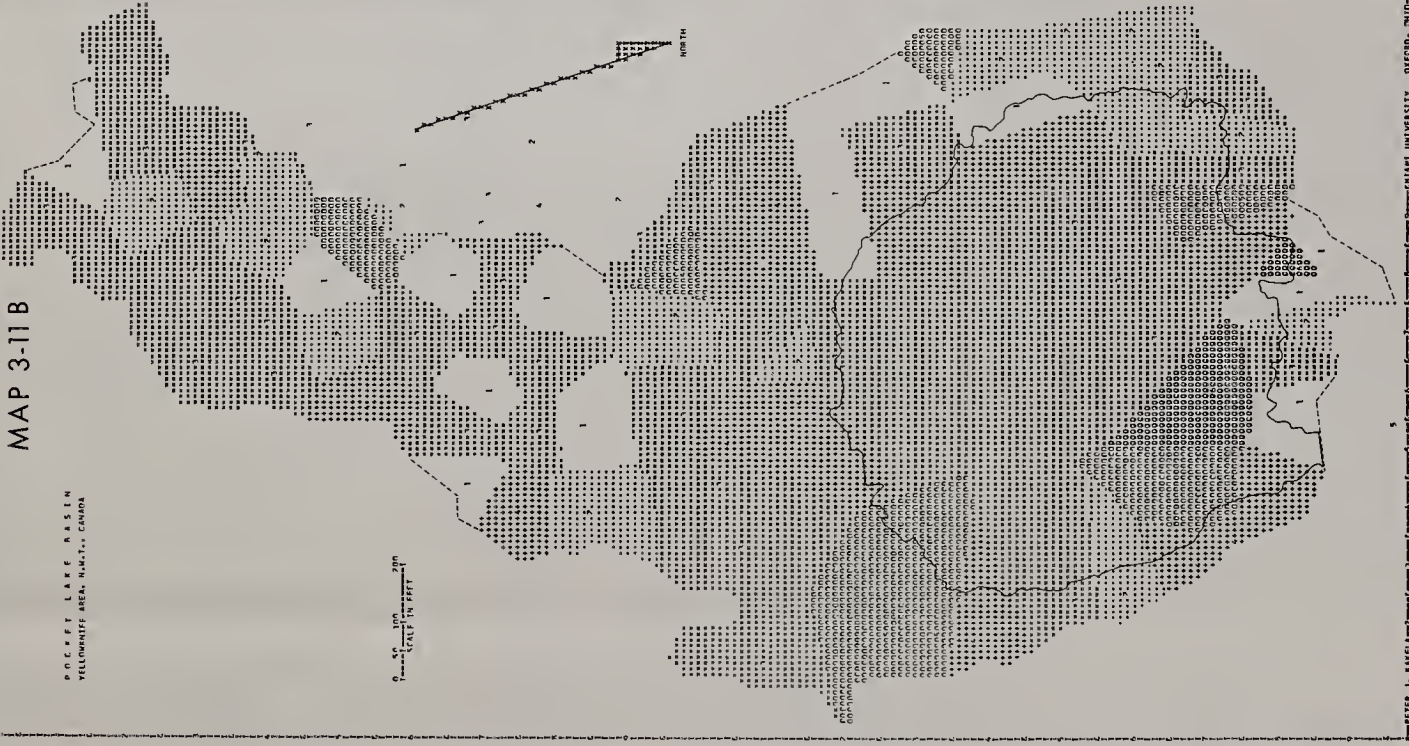


PETER J. KAREL
STAFF
UNIVERSITY OF OHIO, OHIO

MAP 3-II B

POCKET LAKE BASIN
YELLOWHIVE AREA, N.W. 1/4, CANADA

0 10 20
SCALE IN FEET

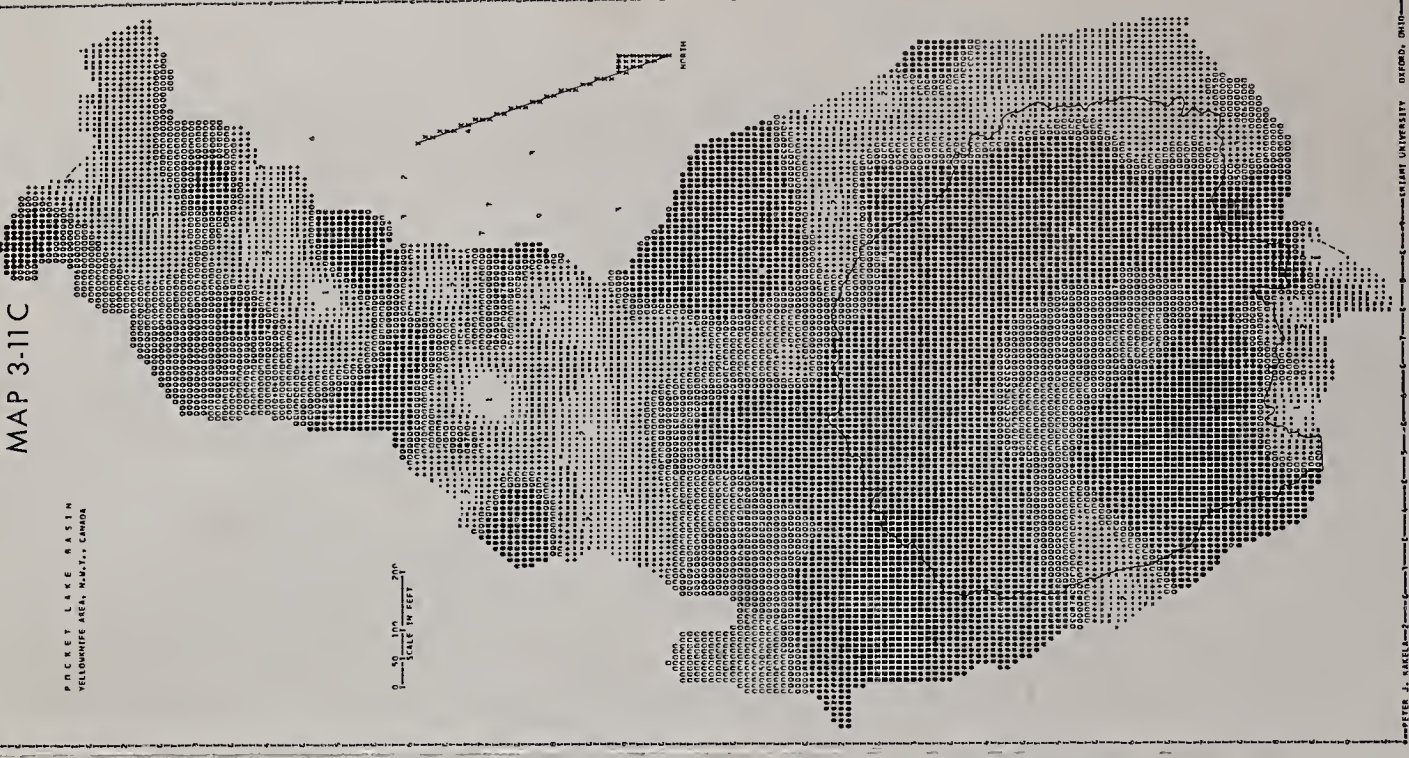
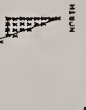


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MAP 3-II C

POCKET LAKE BASIN
YELLOWHIVE AREA, N.W. 1/4, CANADA

0 10 20
SCALE IN FEET



PETER J. KAREL
STAFF
UNIVERSITY OF OHIO, OHIO

third class. A moderate proportion of data point values occurs in the lowest class; however, it has a very restricted areal apportionment on the contour map when compared to the proximal map.

The distribution of specific gravities in Pocket Lake basin is interesting in that it is very different from the two previous distributions of snow depth and water equivalent. The lack of a consistent relationship, direct or inverse, can be illustrated by three cases.

First, the area of highest specific gravity (class six), located just south of the gauge and on the lake ice, is derived from low-middle (on the boundary line between class three and four) water equivalents and low (class three) snow depths. Secondly, the other area of highest specific gravity (class six), located in the central portion of the north shore of Pocket Lake, is derived from middle value (class five) water equivalent and low-middle values (class four) snow depths. The third illustration is the south shore area of Pocket Lake, which was classified as the highest category of water equivalent and also the highest category of depth of snow. It is composed of middle specific gravity values. In this case, the reason for the high water equivalent values is not that the snow was exceptionally dense, but rather, that there was a very large depth of medium density snow.

Map 3-11 C is a contour type map with the April data divided into ten classes of random intervals, each class developed so that an approximately equal number of data points

is included. The slight skewness of the data toward the lower values is indicated by the fact that the first two classes span only 26 per cent of the range, whereas the highest two classes encompass 41 per cent of the range. In both cases, the same frequency of data points (nineteen) was included. By stressing these high and low values, the map illustrates the distribution of the specific gravities on a relative basis. It indicates that in April there were relatively high values of snow specific gravity over the Lake surface and the southeast "valley."

May Measurements

The 278 snow measurements made during May 9-11, 1967, (excluding the single "no snow" observation) provide the basis for the Map 3-12 series of specific gravity maps. Map 3-12 A and Map 3-12 B divide the data into the ten classes with the intervals developed from the total 1967 range of specific gravity measurements. All ten classes are represented by the May data, although the lowest class is a smaller interval than the others because the May minimum value is not as low as the minimum specific gravity measured in April.

The frequency of data points is strongly concentrated toward the middle of the range and grades rather symmetrically toward the highest and lowest classes. In addition to the May data occurring in all ten classes, there is a higher median density value for the May data (class five) than for the April data (class three). Therefore, the May specific

Legend for Map 3-12

SPECIFIC GRAVITY, MAY 9-11, 1967

MOUNT ROSE TYPE SNOW SAMPLER USED
BY LARRY STENE AND PETER KAKELA.

DATA VALUE EXTREMES ARE 0.17 0.50

TOTAL MISSING DATA POINTS 1

A
(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.17	0.17	0.20	0.24	0.28	0.31	0.35	0.39	0.43	0.46
MAXIMUM	0.17	0.20	0.24	0.28	0.31	0.35	0.39	0.43	0.46	0.50

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

0.60	11.08	11.08	10.78	11.08	11.08	11.08	11.08	11.08	11.08	11.08
------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	3	9	27	44	76	53	30	19	9	8

B
(Proximal Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.17	0.17	0.20	0.24	0.28	0.31	0.35	0.39	0.43	0.46
MAXIMUM	0.17	0.20	0.24	0.28	0.31	0.35	0.39	0.43	0.46	0.50

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

0.60	11.08	11.08	10.78	11.08	11.08	11.08	11.08	11.08	11.08	11.08
------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	3	9	27	44	76	53	30	19	9	8

C
(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.17	0.23	0.25	0.28	0.29	0.30	0.32	0.33	0.36	0.40
MAXIMUM	0.23	0.25	0.28	0.29	0.30	0.32	0.33	0.36	0.40	0.50

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

20.15	5.00	8.32	3.35	3.29	5.39	4.49	9.28	10.78	29.94	
-------	------	------	------	------	------	------	------	-------	-------	--

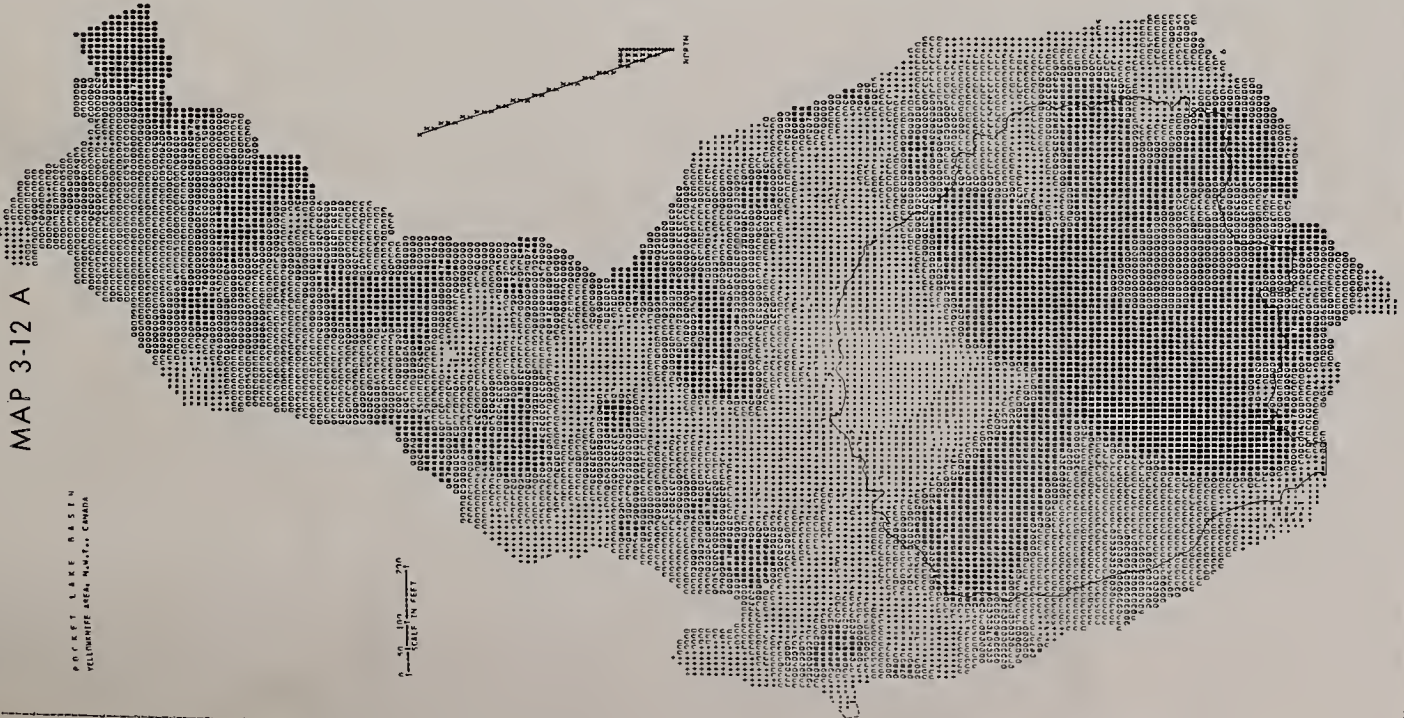
FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	28	11	44	27	20	36	15	37	28	32

MAP 3-12 A

POCKET LAKE BASIN
VELDENHUSE AREA, N.M., U.S.A.

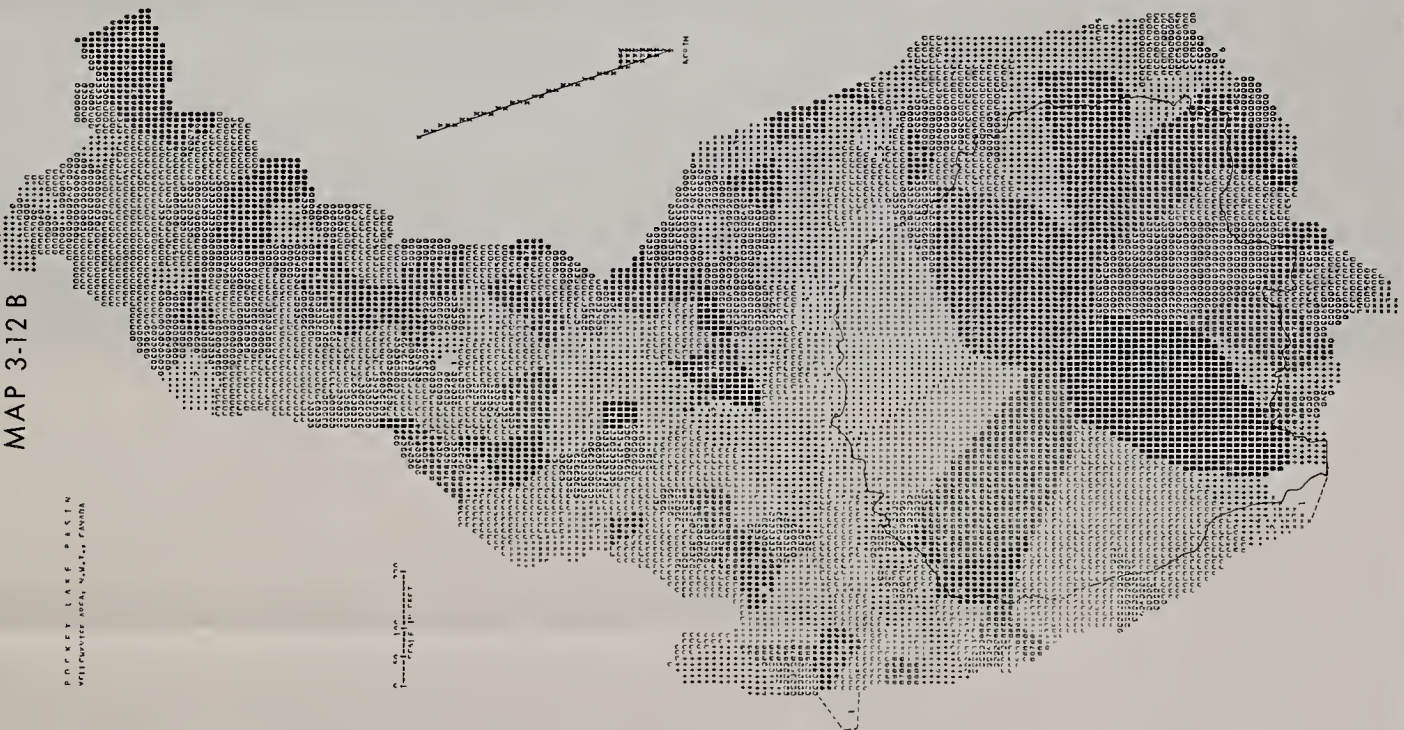
0 100 200
Feet
1:100,000



MAP 3-12 B

POCKET LAKE BASIN
VELDENHUSE AREA, N.M., U.S.A.

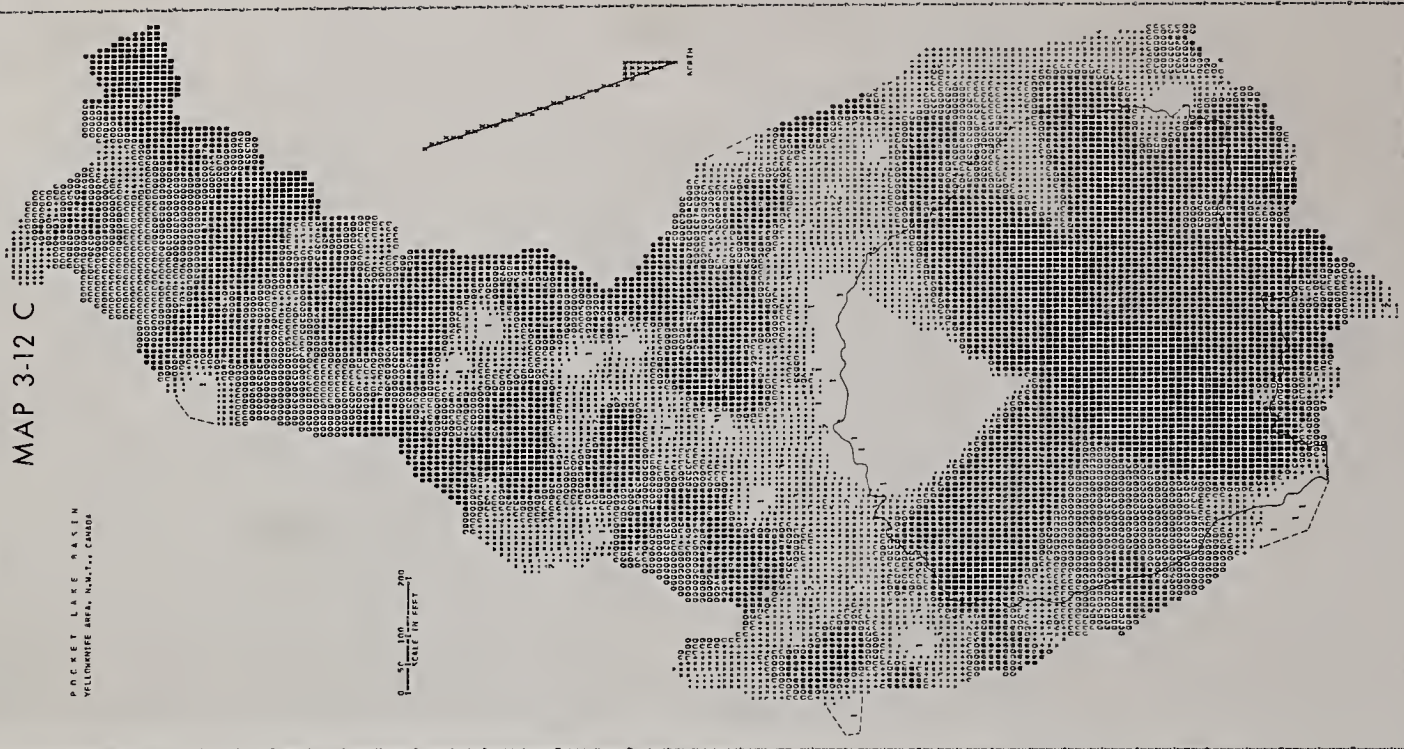
0 100 200
Feet
1:100,000



MAP 3-12 C

POCKET LAKE BASIN
VELDENHUSE AREA, N.M., U.S.A.

0 100 200
Feet
1:100,000



gravity values are, on the average, greater than the April values. This is evident from a comparison of the maps in that the general shade of gray for the May maps (Map 3-12 A and B) is considerably darker than for the April maps (Map 3-11 A and B).

The interpretation of this difference is that some surficial melting of the snow cover occurred between the April and May measurements. Probably most of the surficial meltwater was refrozen at some lower, colder depth in the snowpack. The result was the general increase in density of the snowpack from April to May, exemplified by the increase in mean specific gravity from April (.224) to May (.310).

Map 3-12 C portrays the May specific gravity values divided rather uniformly throughout ten random interval classes. A major portion of the Lake area is classified as having a relatively dense snow cover in May along with several other pockets in the southern portion of the basin. The south shore of Pocket Lake is the largest area of relatively porous snow.

Combined April and May Measurements

The Map 3-13 series was constructed from the total 372 sample values of the snowpack obtained in the spring of 1967. The contour Map 3-13 A and the proximal Map 3-13 B are based on the arithmetic progression of class boundaries which was developed for the specific gravity maps. The frequency of data points in each class is slightly skewed toward the lower

Legend for Map 3-13

SPECIFIC GRAVITY, APRIL 28-29 and MAY 9-11, 1967

DATA VALUE EXTREMES ARE

0.13

0.50

MOUNT ROSE TYPE SNOW SAMPLER USED
BY LARRY STENE AND PETER KAKELA.

TOTAL MISSING DATA POINTS

3

A

(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.13	0.17	0.21	0.24	0.28	0.32	0.35	0.39	0.43	0.46
MAXIMUM	0.17	0.21	0.24	0.28	0.32	0.35	0.39	0.43	0.46	0.50

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	17	29	63	68	74	55	33	16	9	8

B

(Proximal Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.13	0.17	0.21	0.24	0.28	0.32	0.35	0.39	0.43	0.46
MAXIMUM	0.17	0.21	0.24	0.28	0.32	0.35	0.39	0.43	0.46	0.50

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	17	29	63	68	74	55	33	16	9	8

C

(Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.13	0.20	0.23	0.25	0.27	0.29	0.30	0.32	0.35	0.39
MAXIMUM	0.20	0.23	0.25	0.27	0.29	0.30	0.32	0.35	0.39	0.50

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

19.15	7.66	6.25	4.16	5.63	3.80	4.89	7.72	10.57	31.17
-------	------	------	------	------	------	------	------	-------	-------

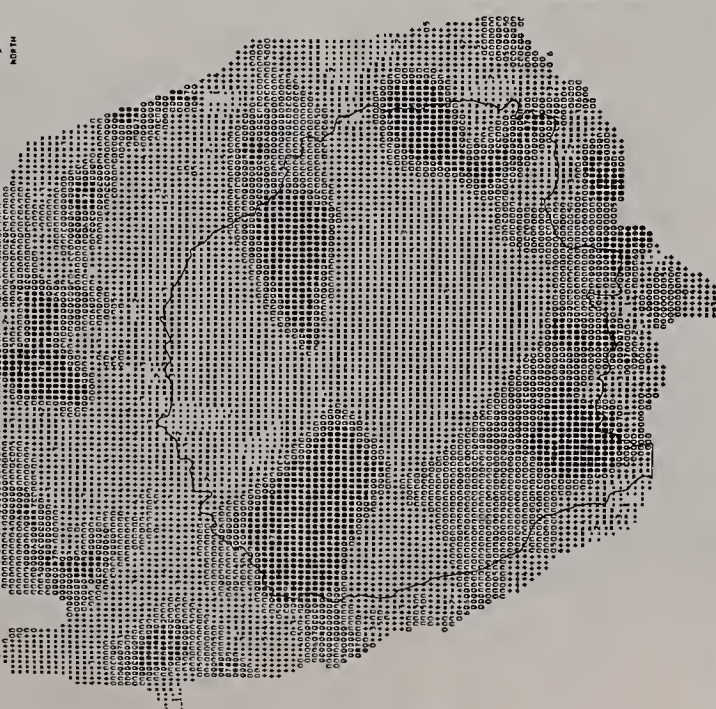
FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	27	36	36	40	35	35	39	40	37	37

MAP 3-13 A

POCKET LAKE BASIN
YELLOWKNIFE AREA, N.W.T., CANADA

0 100 200
SCALE IN FEET

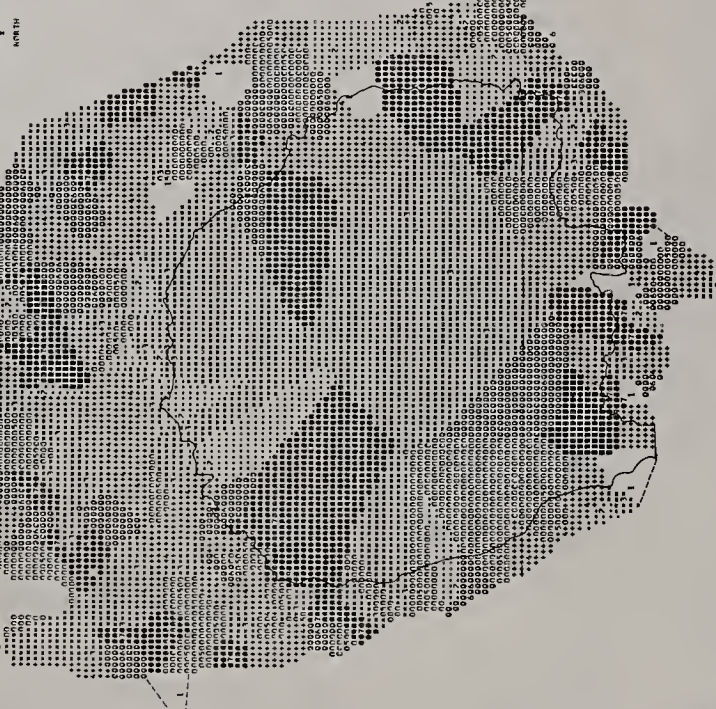


BY J. K. KELLEY, JR. DEPT. OF GEOLOGY, UNIVERSITY OF TORONTO, ONTARIO, CANADA

MAP 3-13 B

POCKET LAKE BASIN
YELLOWKNIFE AREA, N.W.T., CANADA

0 100 200
SCALE IN FEET



BY J. K. KELLEY, JR. DEPT. OF GEOLOGY, UNIVERSITY OF TORONTO, ONTARIO, CANADA

MAP 3-13 C

POCKET LAKE BASIN
YELLOWKNIFE AREA, N.W.T., CANADA

0 100 200
SCALE IN FEET



BY J. K. KELLEY, JR. DEPT. OF GEOLOGY, UNIVERSITY OF TORONTO, ONTARIO, CANADA

classes, which is also indicated by the medium to light-medium gray tone of the two maps. The indication from the maps is that there are several, generally isolated pockets of high specific gravity. These are located primarily on, or at the base of, the bedrock outcrops in the basin.

The distributional pattern of the combined April and May data is a heterogeneous one, comparable in complexity to that of the water equivalent pattern. The complexity of the specific gravity distribution increases from the April values to the May values. This is partly because of an increase in sampling points, but the writer also feels that different amounts of surficial melting for different exposures within the basin contributed significantly to the increase in areal complexity. With surficial melting, water can percolate and refreeze at depth in essentially the same horizontal location. There also can be some horizontal drainage of early meltwater, in that a very light snow cover over a bedrock knoll may melt entirely. Because of very low water retention values for the rock surface, the meltwater could drain over the rock and be incorporated in a snowdrift in a nearby depression. Differential rates of melting at the snow surface would also contribute to variations of the snow density.

Map 3-13 C illustrates the distribution of the relative densities of the spring 1967 snow cover. It is interesting that the snow cover over Pocket Lake was relatively dense in April (see Map 3-11 C) and was classed even denser, on a relative basis, in May (see Map 3-12 C), but the combined

Map 3-13 C indicates that much of the Lake surface is relatively porous. This can be explained by considering the absolute values. In April, when most of the Lake surface samples were taken, the absolute densities were low for the entire basin, but the Lake surface was relatively high with regard to the low value range. Therefore, in the combined map, these April low values were related to a different scale of values on which they appeared relatively low.

The SYMAP program made it practical to map the specific gravities of the snow cover. Specific gravity maps of snow cover have not been published very frequently heretofore. The causes and significance of the distribution of the specific gravity of snow is worthy of further investigation.

Pocket Lake Basin Snow Melt Pattern

The snow cover of a drainage basin does not disappear at a uniform rate during the spring melt period. The melt varies spatially and progresses with time.

Pocket Lake basin is small in area and does not encompass significant relief. Therefore, the variability of the spring snow melt is not dependent upon the variance of temperature with elevation as is so important in mountain and foothill basins. The varying vegetative cover and varying slope aspect and inclination influence the intensity of the incoming solar radiation at the snow surface. These small, localized differences have some influence on the rate of snow melt in Pocket Lake basin. The major cause of the

differential unveiling of the land in spring is the amount of snow that accumulated over different surfaces through the winter.

By examining the spatial variation of the snow melt in Pocket Lake basin, some snow detention relationships can be identified. The areas exposed during the first stages of the spring melt reveal areas that have a combination of light snow accumulation plus surface conditions that receive a high intensity of incoming solar radiation. During the latter part of the melt, the more persistent snowbank areas indicate surfaces where deep drifting occurred along with probably some shelter from intense radiation.

Because of the causal relationship, the snow melt pattern can be used to locate representative snow sampling positions within a basin³¹ which would include high and low, as well as middle range, snow accumulation points. Also, the melt pattern can be related to basin discharge rates for an areal indication of snow melt contribution to runoff.³²

A sequence of photographs of all or parts of Pocket Lake basin is used to illustrate the changing snow cover pattern. (See Figures 3-7 through 3-13.) The first photograph

³¹G. A. McKay, "Precipitation," mimeographed notes for Familiarization Seminar on Principles of Hydrology sponsored by Canadian National Committee for the International Hydrologic Decade and held at the University of Saskatchewan in Saskatoon (September, 1966), p. 2.63.

³²W. U. Garstka, L. D. Love, B. C. Goodell, and F. A. Bertle, Factors Affecting Snowmelt and Streamflow (Washington: U. S. Government Printing Office, 1958), p. 59.

Figure 3-7. October 26, 1966, early autumn snow accumulation. View of bedrock knoll just west of gauged Lake outlet with Pocket Lake and south shore in upper left.

Figure 3-8. April 26, 1967, snow cover. View of gauge and east shore of Pocket Lake. Taken by Larry Stene.



Figure 3-7



Figure 3-8

Figure 3-9. May 9, 1967, snow cover in Pocket Lake basin.

Figure 3-10. May 13, 1967, snow cover in Pocket Lake basin.



Figure 3-9

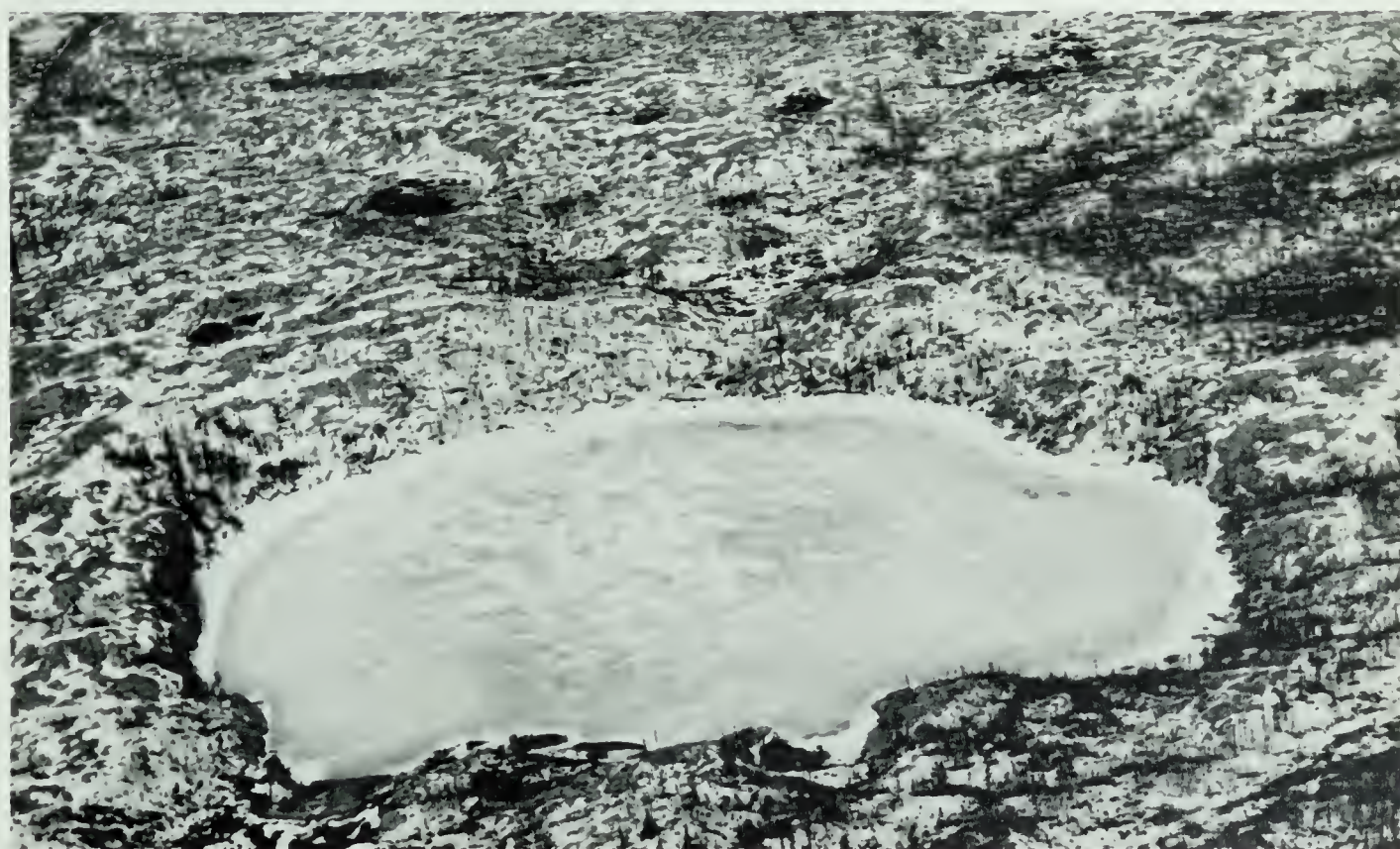


Figure 3-10

Figure 3-11. May 18, 1967, snow cover. View of south shore of Pocket Lake.

Figure 3-12. May 22, 1967, snow cover. View of south shore of Pocket Lake.



Figure 3-11



Figure 3-12

Figure 3-13. May 26, 1967, View of Pocket Lake basin. Looking south with Giant Yellowknife Mine buildings just beyond basin. In background is Yellowknife Bay of Great Slave Lake and Yellowknife "Old Town" on peninsula and island; Yellowknife "New Town" in far upper right. Taken by John Light.



Figure 3-13

of the series was taken on October 26, 1966, when an average of 3.5 inches of powdery snow had already collected on the ground surface. At this time, the five inches of lake ice also supported several inches of snow and certainly the 1966-67 water year snow cover had begun. At the other extreme, the ice cover on Pocket Lake was observed to be completely melted on June 1, 1967.

The other six photographs in the melt series were taken during the spring of 1967 and illustrate successive stages of melt in the basin. With the exception of Figures 3-7 and 3-8, the pictures were taken from the air. It is interesting to note that the general melt pattern does not reveal many major, extensive snowdrifts within the basin. The most pronounced one that does occur is located along the shore area of the Lake, especially on the southern side. The other conspicuous feature indicated by the photographic sequence is the dispersed pattern of the smaller snowbanks. The smaller banks are located mostly in sharp depressions in the bedrock or at the break in slope where the bedrock descends to a flat, moss covered basin. The residual banks appear to be related more directly to these ground surface irregularities than to the tree or bush areas.

Some interpretations of the snow melt pattern can be made from the photographs. First, the limited extent of major drifts might be caused by the small total snow precipitation received in the region. Another interpretation is that a larger proportion of relocation of snow during the winter

must occur on the bedrock outcrops than on the flatter, moss covered areas. It is felt that the relocation of snow on the bedrock is over short distances, i.e., from bedrock knoll to bedrock "nitch," and that this is the major course of drifting in Pocket Lake basin. There were no indications of net import or export of snow from the basin as a whole.

Snowbank Melt Pattern

Six snowbanks were investigated in some detail throughout the melt period. From two to fifteen samples were taken in each snowbank, depending upon the size of the bank. These samples were replicated as closely as possible at time intervals during the melt. The location of the snowbanks is presented on Map 3-14.

A sequence of terrestrial photographs was taken of most of the snowbanks, two of which are presented here. The snowbank located at the height of land within Pocket Lake basin (Bank One) is pictured in Figure 3-14. Bank Two, located above the steep, east shore of Pocket Lake, is shown from May 10 through May 22, 1967, in the six photos of Figure 3-15.

The mean values for measured specific gravity and depth of water equivalent of each snowbank were plotted (Figure 3-16) against the dates of observation. As expected, there is a sharp decline in the mean water equivalent values and its constancy is interrupted only by a decrease in rate from May 18 to May 20.

MAP 3-14

SNOWBANKS SAMPLED IN POCKET
LAKE BASIN, SPRING 1967



Figure 3-14. Melt pattern of snowbank near height of land in Pocket Lake basin (Bank One).



a. May 11



b. May 15



c. May 18



d. May 20



e. May 22

Figure 3-14

Figure 3-15. Melt pattern of snowbank above steep,
east shore of Pocket Lake (Bank Two).



b. May 10



b. May 12



c. May 15



d. May 18



e. May 20



f. May 22

Figure 3-15

1967 SNOWBANK SPECIFIC GRAVITY AND WATER EQUIVALENT

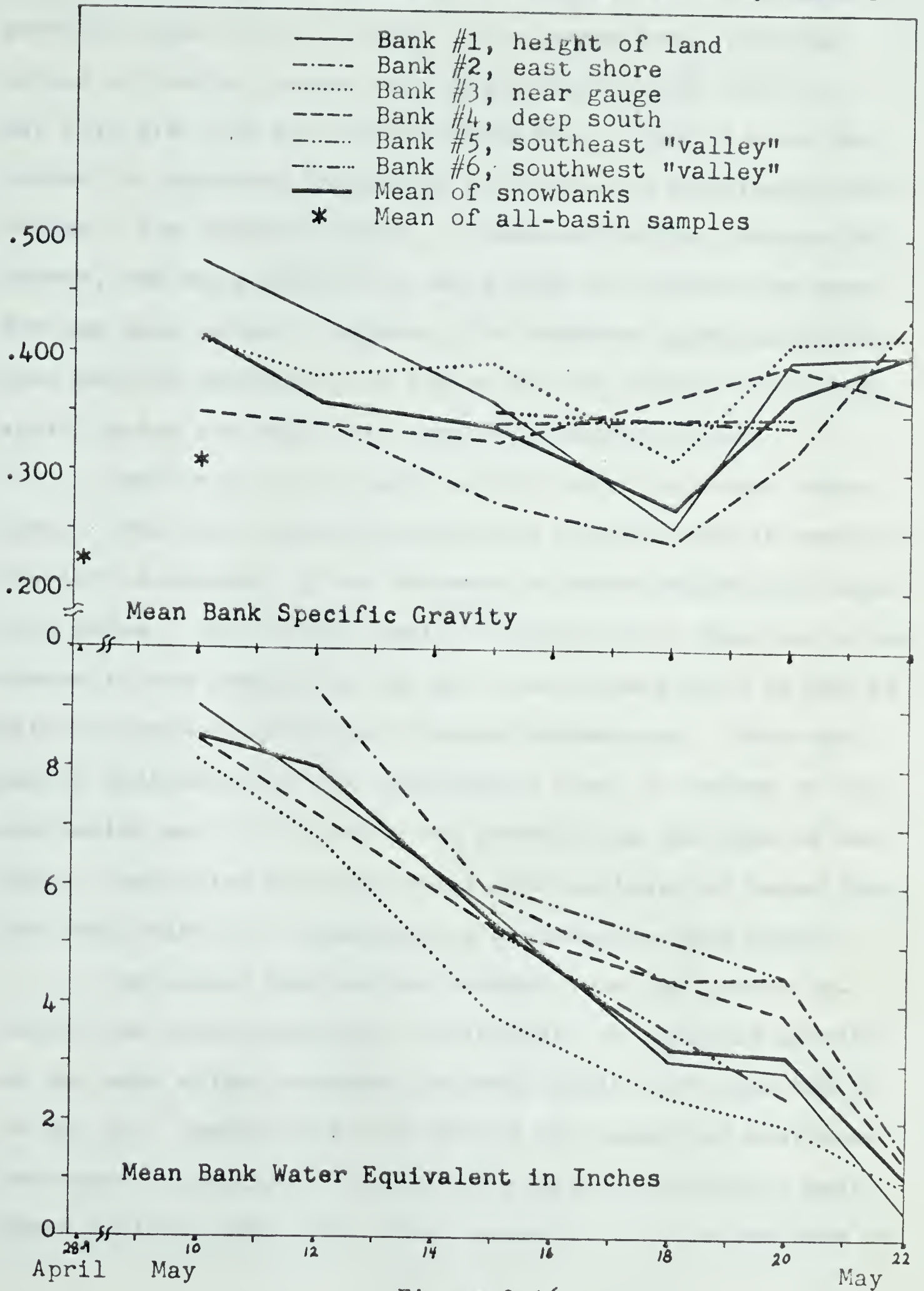


Figure 3-16

The mean specific gravity values for the snowbanks exhibit a more curious trend. As a comparison, the mean values of the basin-wide survey for April 28-29 and for May 9-11 are .224 and .310 respectively. There is, as expected, an increase in density of the snow as surficial melt begins. The snowbank means, as measured during the May 9-11 survey, are even greater in value than the basin-wide mean for the same period. However, the snowbank specific gravities tend to decrease to a low on May 18, before increasing again during the very last stages of their existence.

Two interesting points can be mentioned about these plots. The first point involves the curious drop in specific gravity as related to the decrease in water equivalent depletion rates. This relationship indicates that there was a decrease in the density of the snowbanks from May 15 to May 18 with a continued decrease in water equivalents. This was partly influenced by the addition of some .12 inches of precipitation on May 17, which was probably in the form of wet snow. There also must have been some draining of water from the banks without a commensurate decrease in snow depth.

The second implication deduced from the graphs involves the relationship of the increase in specific gravity to the very slight decrease in water equivalent from May 18 to May 20. During this time period the snowbanks must have increased in density, but with very little consequent melt-water drainage from them. The causes of the fluctuations of

snow specific gravities late in the melt process deserves more research.

With regard to the absolute values of specific gravity, the snowbanks measured during the melt period were less dense than expected. Once the snow has been converted to the coarse structured ripe snow (see Figure 3-17) by warmer temperatures it has been noted to have "a remarkably uniform density, as observed throughout the world, of from 45 to 50 per cent."³³

The low specific gravity measurements for the Pocket Lake snowbanks may partially be explained by the fact that the samples were taken as cores through the entire snowbanks. There was an observed gradation from the surface to the base of the banks. (See Figure 3-18.) The surface was generally composed of a very coarse grained, but porous type of snow. At greater depths, there was more compactness of the coarse grains and much more free water held in suspension. The basal layers of many of the snowbanks were composed of ice. Often, toward the latter part of the melt season, free water was observed to be discharging from the snowbanks as dripping water released at this basal ice layer.

Thus, there was variance in the density through the snowbanks with only a few individual samples reaching the

³³W. U. Garstka, "Snow and Snow Survey," in Handbook of Applied Hydrology, ed. by V. T. Chow (New York: McGraw-Hill Book Company, 1964), sec. 10, p. 9.

Figure 3-17. Ripe snow.

Figure 3-18. Transition from ripe snow to ice to
dripping water at base of a snowbank.



Figure 3-17



Figure 3-18

ripe snow densities throughout.³⁴ On the last day of snow-bank sampling (May 22) the mean value of water equivalent detained in the banks was about one inch. The specific gravity measurements in the residual snow were remarkably uniform and averaged .401.

1968 Pocket Lake Basin Measurements

Introduction

During the early spring of 1968, the snow cover of Pocket Lake basin was again sampled intensively. The 144 samples were obtained on April 16 and 17 by Mr. E. Spence.³⁵ The sample values of snow water equivalent, snow depth, and specific gravity were mapped by the writer with the use of the SYMAP program. A series of selected maps is presented and discussed for each of the variables.

These maps are interesting for two reasons. First, they permit spatial comparisons to be made with the maps of the 1967 snow sample values. Secondly, the 1968 maps illustrate the spatial portrayal by the SYMAP technique of data collected and supplied in numerical form only. That is, the 1968 survey did not include the field evaluation of spatial

³⁴ During the snow survey for the entire basin, a few specific gravity measurements were as high as .500. Some of these actually had free water dripping from the sampling tube.

³⁵ The 1968 snow sample values and the SYMAP coordinate locations of each sampling site are also listed in Appendix A.

representation of the sample measurements that was done for 1967 Field Map (Map 3-1).

Water Equivalents

The Map 3-15 series depicts the distribution of the water equivalent values obtained from the 1968 snow survey. Map 3-15 A is a contour map with ten classes, each class encompasses 10 per cent of the data range. Because the data extend from 0.00 to 10.00 inches of water equivalent, the class intervals occur at the whole inch. The data point values are most frequent in the 2.01 through 5.00 inch classes.

Map 3-15 B is a proximal map developed from the identical data and subdivisions as the previous map. The distinction between value areas is marked. The area allotted to the high and low value data points is larger than for the middle values when compared to the previous contour type map.

The contour Map 3-15 C has ten randomly spaced classes, each of which contains approximately the same frequency of data points. This map spreads the low middle concentration of values more evenly through all the classes, and thus, tends to areally stress the high sample values to a greater extent than do the other maps of this series.

The 1968 pattern of snow water equivalents in Pocket Lake basin corresponds in part to the 1967 distribution. (See Map 3-4 and Map 3-5 series.) The high value pockets around the shore of Pocket Lake and the relatively low values

Legend for Map 3-15

WATER EQUIVALENTS, APRIL 16-17, 1968

MOUNT ROSE TYPE SNOW SAMPLER USED BY
TED SPENCE IN CONDUCTING SNOW SURVEY.DATA VALUE EXTREMES ARE 0.0 10.00
INCHES OF WATER EQUIVALENTA
(Contour Type Map)ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.0	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01	9.01
MAXIMUM	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01	9.01	10.00

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

10.10	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	9.90
-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	.....	=====	++++++	00000000	00000000	00000000	00000000	00000000	00000000
FRQ.	9	12	36	35	28	13	7	3	0	1

B
(Proximal Type Map)ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.0	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01	9.01
MAXIMUM	1.01	2.01	3.01	4.01	5.01	6.01	7.01	8.01	9.01	10.00

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

10.10	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	9.90
-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	.....	=====	++++++	00000000	00000000	00000000	00000000	00000000	00000000
FRQ.	9	12	36	35	28	13	7	3	0	1

C
(Contour Type Map)ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

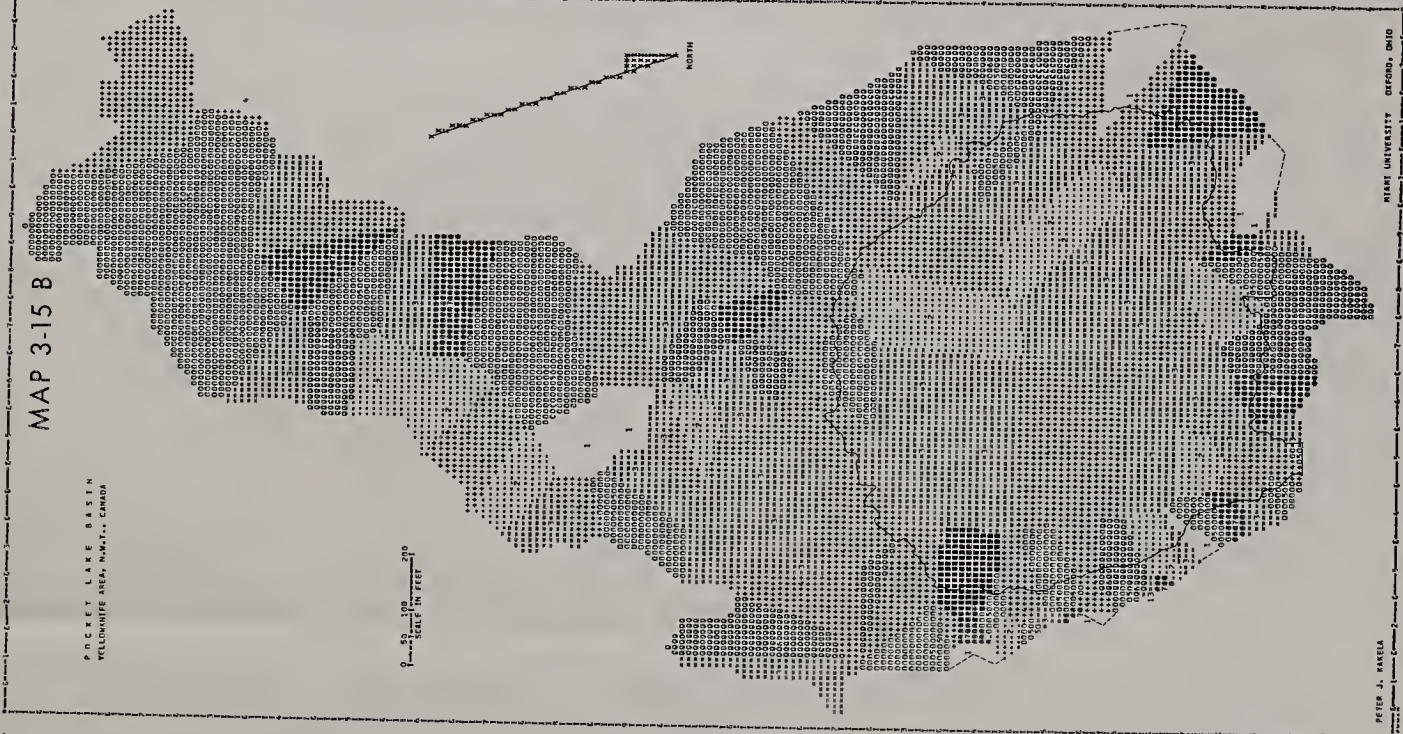
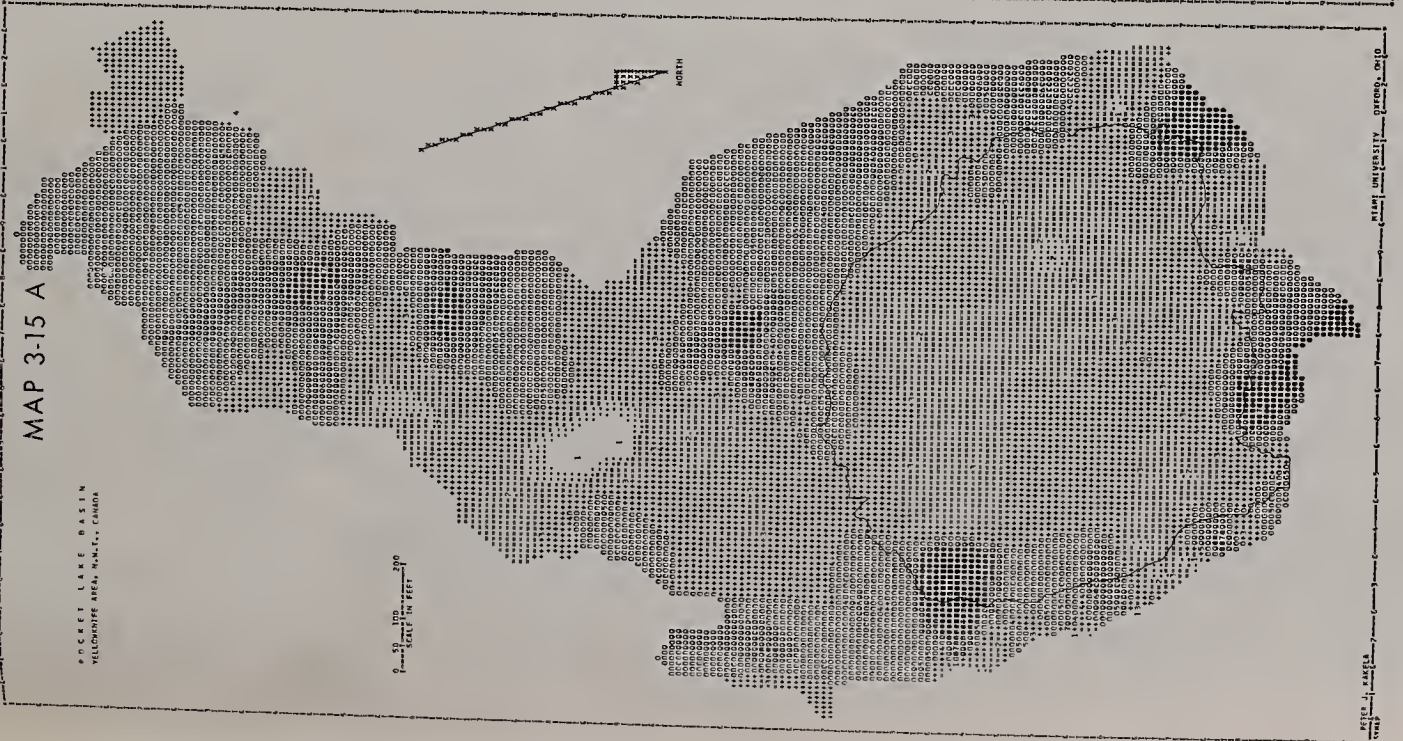
MINIMUM	0.0	1.50	2.50	3.00	3.50	4.00	4.50	5.00	5.50	6.50
MAXIMUM	1.50	2.50	3.00	3.50	4.00	4.50	5.00	5.50	6.50	10.00

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

15.00	10.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	10.00	35.00
-------	-------	------	------	------	------	------	------	------	-------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	.....	=====	++++++	00000000	00000000	00000000	00000000	00000000	00000000
FRQ.	9	12	5	31	10	25	7	21	13	11



for the Lake surface are similar for both years. More samples were taken of the Lake snow cover in 1968 than in 1967, and therefore, the Lake pattern is probably more accurately depicted by the Map 3-15 series. The patterns over the Lake vary considerably. The 1967 maps indicate a high water equivalent area on the western part of the Lake surface, whereas the 1968 maps indicate a relatively low pocket in the same area. This portion of the Lake was sampled in both years, and thus the writer suggests that there was a different snow accumulation pattern on the Lake surface in 1968 than was observed in 1967.

There are some similarities of highs and lows for the rest of the basin, but there are some marked differences too. The variance of pattern in the southern portion of the basin is probably related to the difference in sampling site locations for the two years as much as it is related to the difference in drifting pattern.

Depth of Snow

The 1968 snow depth values are displayed by the Map 3-16 series. Map 3-16 A is a contour map with the ten classes having the identical boundary values as those established for the 1967 data. (See Map 3-8, Map 3-9, and Map 3-10 series.) The 1968 values are concentrated in the medium high classes and the dark gray tone of Map 3-16 A illustrates this spatially. The Lake is the largest area of shallow snow accumulation.

Legend for Map 3-16

SNOW DEPTH , APRIL 16-17, 1968

MOUNT ROSE TYPE SNOW SAMPLER USED BY
TED SPENCE IN CONDUCTING SNOW SURVEY.

DATA VALUE EXTREMES ARE

0.0 66.00
INCHESA
(Contour Type Map)ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.0	3.33	6.67	10.00	13.33	16.67	20.00	23.33	26.67	ABOVE
MAXIMUM	3.33	6.67	10.00	13.33	16.67	20.00	23.33	26.67	30.00	30.00

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11
-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	H
SYMBOLS	1	2	3	4	5	6	7	8	9	H
FREQ.	6	2	3	16	20	13	27	31	13	13

B
(Proximal Type Map)ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.0	3.33	6.67	10.00	13.33	16.67	20.00	23.33	26.67	ABOVE
MAXIMUM	3.33	6.67	10.00	13.33	16.67	20.00	23.33	26.67	30.00	30.00

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11
-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	H
SYMBOLS	1	2	3	4	5	6	7	8	9	H
FREQ.	6	2	3	16	20	13	27	31	13	13

C
(Contour Type Map)ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

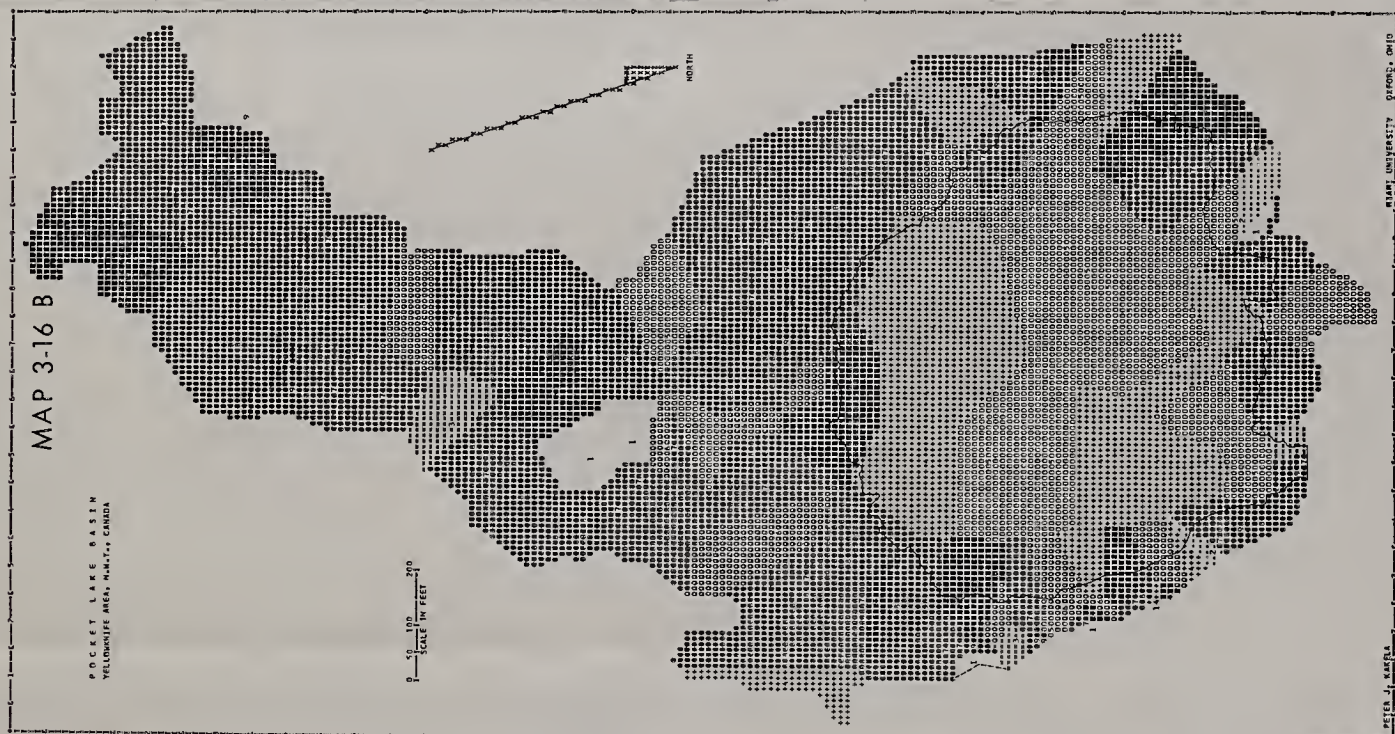
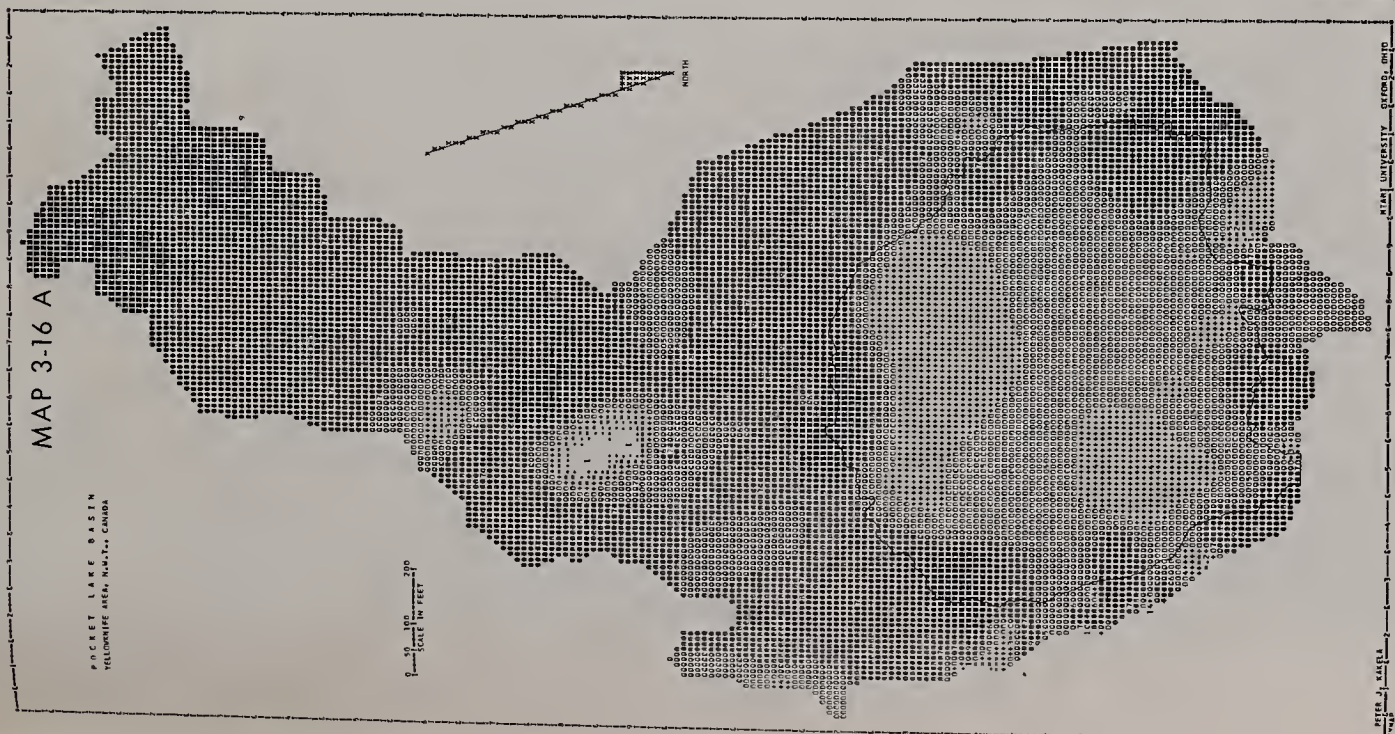
MINIMUM	0.0	11.00	14.00	15.00	19.00	21.00	23.00	25.00	26.00	30.00
MAXIMUM	11.00	14.00	15.00	16.00	21.00	23.00	25.00	26.00	30.00	66.00

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

16.67	4.55	1.52	6.06	3.03	3.03	3.03	1.52	6.06	54.55
-------	------	------	------	------	------	------	------	------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	13	14	9	16	13	14	21	6	23	15



Map 3-16 B is a proximal map of the same data subdivided into the identical classes as the previous map. Again with the proximal type of map, greater contrast of tone (and thus values) is portrayed; however, it appears that the lower value areas are emphasized slightly more than the higher value areas.

The ten random interval classes of Map 3-16 C divide the data points into nearly equal frequencies. This tends to stress the lower snow depth values spatially and bring out the relatively shallow snow cover that persisted on the bedrock knolls as well as the Lake surface.

Snow Specific Gravities

The 1968 specific gravity measures of the snow cover are presented in the Map 3-17 series. Map 3-17 A is a contour map in which each class includes 10 per cent of the data range. The highest specific gravities occur along the south facing slopes of the northern shore of Pocket Lake, which could indicate some selective surficial melting because of the slope aspect. The snow cover on the Lake is denser proportionately than most of the upland surface. This could indicate some surface melting and refreezing at depth or, more probably, lateral drainage of early meltwaters from surrounding shore areas.

Map 3-17 B is a proximal map of the identical values and classes as used in the previous map. The proximal map brings out the contrast of data point values throughout the

Legend for Map 3-17 SPECIFIC GRAVITY, APRIL 16-17, 1968

MOUNT ROSE TYPE SNOW SAMPLER USED BY
TED SPENCE IN CONDUCTING SNOW SURVEY.

DATA VALUE EXTREMES

0.08

0.40

TOTAL MISSING DATA POINTS

5

A (Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.08	0.11	0.14	0.17	0.21	0.24	0.27	0.30	0.34	0.37
MAXIMUM	0.11	0.14	0.17	0.21	0.24	0.27	0.30	0.34	0.37	0.40

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	7	19	20	31	28	21	7	3	1	2

B (Proximal Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

MINIMUM	0.08	0.11	0.14	0.17	0.21	0.24	0.27	0.30	0.34	0.37
MAXIMUM	0.11	0.14	0.17	0.21	0.24	0.27	0.30	0.34	0.37	0.40

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	7	19	20	31	28	21	7	3	1	2

C (Contour Type Map)

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY

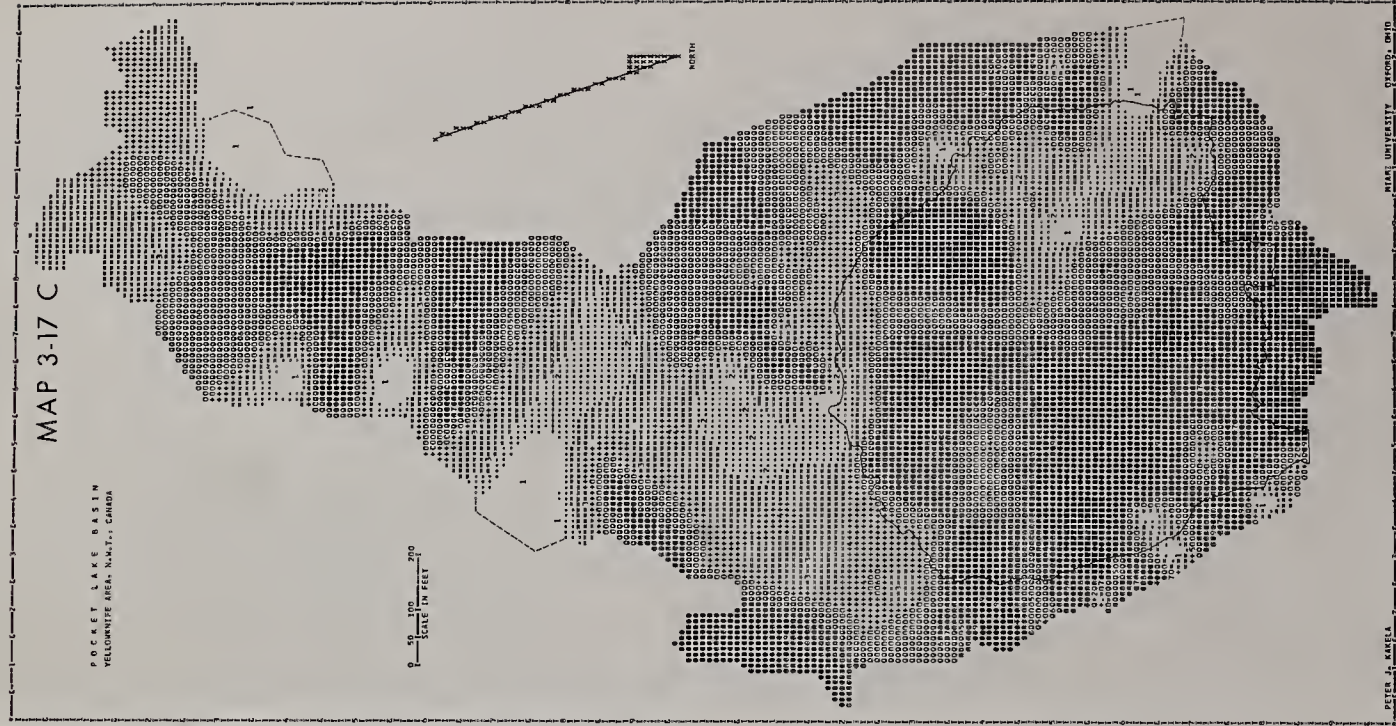
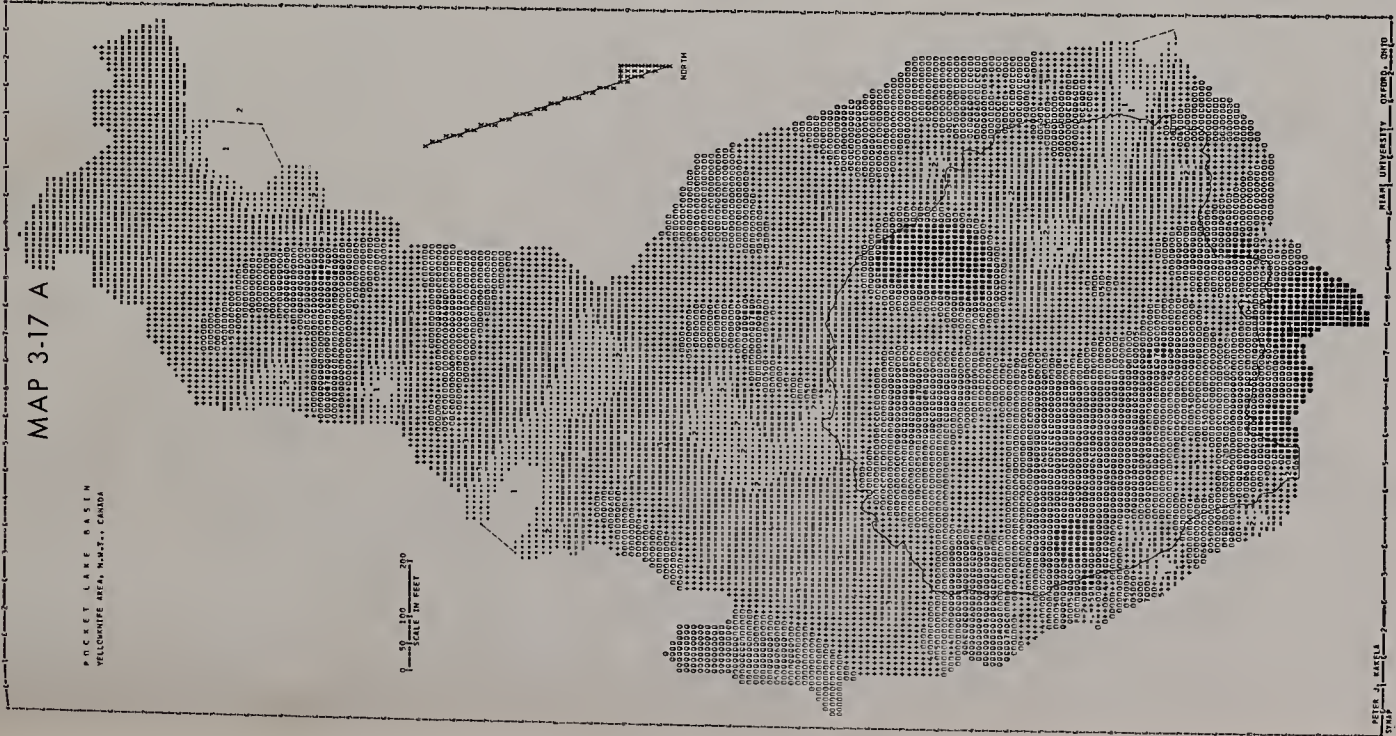
MINIMUM	0.08	0.13	0.14	0.17	0.18	0.19	0.21	0.23	0.25	0.27
MAXIMUM	0.13	0.14	0.17	0.18	0.19	0.21	0.23	0.25	0.27	0.40

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

15.12	5.56	7.16	4.04	4.23	5.25	6.48	5.86	5.86	40.43
-------	------	------	------	------	------	------	------	------	-------

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6	7	8	9	10
SYMBOLS	1	2	3	4	5	6	7	8	9	10
FREQ.	13	14	15	14	12	14	11	15	16	15



basin. The values tend to be concentrated in the low to middle classes.

With random class intervals, Map 3-17 C portrays the 1968 specific gravity values on a relative basis. Each class has almost the same number of data points within it, and therefore, more spatial emphasis is placed on the denser value classes than was true in the two preceding maps.

In absolute terms, the 1968 snow depths were greater than those of the 1967 spring survey, although the water equivalents contained in the snow cover were more nearly equal. Therefore, the snow sampled in 1968 must have been more porous than that of 1967, and this is substantiated by the specific gravity values. The most probable explanation of this is that surficial melting and subsequent refreezing had occurred before or during the 1967 snow survey and that the 1968 survey preceded any significant melting.

CHAPTER IV

ANALYSIS OF WATER BALANCE CALCULATIONS BASED UPON THE THORNTHWAITE PROCEDURE

Introduction

Evaluation of the Yellowknife Area climatic water balance as calculated by the Thornthwaite procedure is presented in this chapter. The evaluation is based upon a comparison of derived runoff values with the measured, Yellowknife River discharge values. In addition, runoff values calculated by means of a modified Thornthwaite procedure and various manipulations of precipitation data are correlated with the measured discharge data in an attempt to discover relationships. Therefore, the chapter includes measured discharge data, calculated water balance values using the Thornthwaite procedure, and statistical correlations of variables. The relationships are discussed and numerous water balance equations are presented to illustrate some seasonal and site variations that occur in the Yellowknife Area.

Yellowknife River Discharge

Data

The complete record of discharge measurements made in the Yellowknife River basin is presented in Table

IV-1.¹ The most pertinent values to the present study are the annual discharge measures by water year for the Yellowknife River at the inlet to Prosperous Lake (station 7SB₃) which are expressed in inches of depth over the drainage area for the years 1942-43 through 1966-67. This set of data covers the identical twenty-five year period for which the Yellowknife Airport meteorological station observations are available. Also, the data are expressed in terms which are comparable to precipitation measurements and other calculated water balance variables (inches of depth over the land surface).

Accuracy of Streamflow Data

Most of the streamflow data for the Yellowknife River were obtained by the use of a staff gauge to measure the height of the river. These measurements were converted to volumes of flow by an appropriate discharge rating curve that was prepared for each station through a series of accurate discharge measurements for various staff height conditions. The staff form of measuring the height of the river is not as accurate a method as an automatic water-level recording gauge that measures continuous stream height. The primary reason for the lower accuracy of the staff gauge is that it is

¹ Descriptions of the four stream gauging stations that have been maintained in the Yellowknife River basin, and for which data are presented in Table IV-1, are presented in Appendix B. Also, the slight computation adjustments made to the published data are explained more fully in Appendix B.

TABLE IV-1
DISCHARGE DATA FOR THE YELLOWKNIFE RIVER

Water Year	Yk. R., Outlet from Bluefish Lake Dam; 7SB ₅		Yk. R., Power Diversion Site Y ₂ ; 7SB ₆		Yk. R., Inlet to Prosperous Lake; 7SB ₃ , (Area: 4,350 sq. miles, or 2,784,000 acres)	Yk. R., Outlet of Prosperous Lake; 7SB ₂ , (Area: 6,300 sq. miles or 4,032,000 acres)
	Acre Feet		Acre Feet		Acre Feet	Depth in Inches on Drainage Area
37-38						946,000
38-39					265,600 p	459,000
39-40					208,900 p	391,500
40-41					552,600 p	1.17
41-42	174,500	+	265,100	=	439,600 o	1.89 o
42-43	207,980	+	256,750	=	464,730 d	2.00
43-44	472,100	+	197,200	=	669,300	2.88
44-45	205,300	+	201,000	=	406,300	1.75
45-46	322,900	+	243,700	=	566,600	2.44
46-47	224,800	+	299,960	=	524,760 d	2.26*
47-48	260,830	+	282,400	=	543,230	2.34
48-49	664,700	+	270,420 d	=	935,120 d	4.03
49-50					456,200	1.97
50-51					472,400	2.04
51-52					861,300	3.71
52-53					572,300	2.47
53-54					689,400	2.97
54-55					716,100	3.09
55-56					468,600	2.02
56-57					850,400	3.67
57-58					905,200	3.90
58-59					1,053,000	4.54
59-60					1,195,000	5.15
60-61					553,700	2.39
61-62					438,800	1.89
62-63					888,700	3.83
63-64					1,423,000	6.13
64-65					674,400	2.91
65-66					596,000	2.57
66-67					646,200	2.79
Total	2,533,110		2,025,510		(25 years) 17,570,740	(25 years) 75.74
Mean	316,639		253,189		702,830	3.03
						1,796,500
						598,833
						5.36
						1.79

p = partial year's record available only, therefore not included in calculations of Total or Mean.
o = complete 1941-42 year, but omitted from Total and Mean in order that identical 25 year coverage be maintained with meteorological data.
* = calculated value, using acre feet discharge and drainage basin area, worked out to be slightly different than published value for this year. Calculated value presented here.
d = slightly different value derived by totaling published monthly quantities, than was published as the sum. Totalled value presented here.

Source: "Surface Water Supply of Canada, Arctic and Western Hudson Bay Drainage, and Mississippi in Canada," Water Resources Papers: 84, 88, 92, 97, 101, 105, 109, 113, 117, 121, 125, 127, 132, 135, 138, 141, and 145, (Ottawa: Queen's Printer and Controller of Stationery), plus personal communication by letter, R. D. May, District Engineer, Water Survey of Canada, Inland Waters Branch, Department of Energy, Mines and Resources of Canada, June 5, 1968.

usually read only once a day, whereas the recording gauge gives continuous readings. The staff gauge reading is not a consistent measure of the maximum, minimum, or mean height for the day, but the readings are employed statistically as the mean daily level.

There were also notations of shifting channel controls and, of course, winter icing conditions, both of which tend to impair the accuracy of discharge measurements. Shifting channel controls were mentioned only in the early years of measurement, but icing is an annual problem.

Although most of the streamflow measurements made on the Yellowknife River were derived from staff gauge readings and some disrupting conditions were encountered, the readings are the only discharge data available for the Yellowknife Area.² It must be remembered that in this relatively undisturbed environment there have been few human alterations to the "natural" hydrologic conditions. In other words, there is no consumption of water for irrigation or water supply, and little human influence on the land surface conditions or sub-surface moisture conditions is present. The diversion of water to the hydroelectric plant that does take place on the Yellowknife River is gauged and calculated as part of the total discharge. Also, it is doubtful whether there is any

²Discharge data are available for other Subarctic rivers that drain into the Mackenzie River from the western margin of the Canadian Shield (i.e., Snare, Emile, Lockhart, and Taltson), but these rivers are outside the Yellowknife Area as defined in this thesis.

significant movement of groundwater into or out of the basin in this region of crystalline Shield bedrock which is susceptible to permafrost development.³

Therefore, the streamflow measurements must be considered as an important actual measurement of a water balance variable, and it is fortunate that the records for Yellowknife River are so lengthy.

Importance of Streamflow

Streamflow is an important variable of the water balance for several reasons. First, it is an areal measurement of water (i.e., the total surplus water running out of a drainage basin) rather than a point observation to which precipitation, evapotranspiration, or soil moisture, for example, are usually limited. R. K. Linsley, M. A. Kohler, and J. L. H. Paulhus suggest that:

Streamflow is the only portion of the hydrologic cycle in which moisture is so confined as to make possible reasonably accurate measurements of the volumes involved. All other measurements in the hydrologic cycle are, at best, only inadequate samples of the whole.⁴

A second streamflow characteristic of importance is

³L. V. Brandon, Groundwater Hydrology and Water Supply in the District of Mackenzie, Yukon Territory, and Adjoining Parts of British Columbia, Paper 64-39 of the Geological Survey of Canada, Department of Mines and Technical Surveys (Ottawa: Queen's Printer and Controller of Stationery, 1965), p. 25.

⁴R. K. Linsley, M. A. Kohler, and J. L. H. Paulhus, Applied Hydrology (New York: McGraw-Hill Book Co., 1949), p. 182.

that it is a dependent variable in the water balance because it is a residual quantity of the initial water supply (precipitation) after evaporation and transpiration have taken their share and storage change has resulted. Therefore, if there is an accurate measure of the original source of water (precipitation) and the amount that is excess to the region (streamflow), then there is quite a concise estimate of the total water available for the in-between processes of evaporation, transpiration, and storage change.

Thirdly, because streamflow from a large basin area is concentrated into a relatively small channel, the valid location of a "well exposed" gauging site is easy to establish and the flow volumes as a result, are comparatively large. The fact that streamflow is easily observed visually (compared to evapotranspiration, for example) and that quantitative evaluation of fluid flow has been important for irrigation and industry, have both contributed to the development of precision in flow measurement gauges. The result is that streamflow is one of the most accurately measured variables of the water balance and the measured values presented here will be relied on heavily.

Therefore, in the subsequent analysis the Yellowknife River discharge measurements are considered the dependent variable (X_1) with which other data are correlated. First, the runoff values derived from calculations based on the Thornthwaite procedure are correlated with the measured discharge in order to assess how accurately they predict

discharge on an annual water year basis. Secondly, other variables are correlated with measured discharge in an attempt to identify relationships more fully.

Calculated Water Balance

Thornthwaite Procedure

Using the mean monthly precipitation and mean monthly temperature values published⁵ for the Yellowknife Airport meteorological station, the water year annual climatic water balances were calculated essentially⁶ according to the Thornthwaite procedure as presented in 1957.⁷ A soil moisture retention capacity of one inch was used in the calculations for two reasons. First, this is very close to the mean spring retention capacity calculated for the Pocket Lake basin (.83 of an inch) as portrayed on Map 2-5. Secondly, the twenty-five year mean calculated runoff (3.81 inches), using a one inch soil moisture retention capacity, is reasonably close to

⁵ Canada, Department of Transport, Meteorological Branch, Monthly Record (Ottawa: Queen's Printer and Controller of Stationery, 1942-1967).

⁶ Because of the small soil moisture retention capacities, the rate of soil moisture withdrawal was considered to be consumed at the demand rate rather than tapering off as soil moisture storage approached zero.

⁷ C. W. Thornthwaite and J. R. Mather, Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance, Publications in Climatology, Vol. X, No. 3 (Centerton, N. J.: Drexel Institute of Technology, Laboratory of Climatology, 1957), pp. 185-311.

the mean measured discharge from the Yellowknife River basin (3.03 inches) for the same time period.

There are some major shortcomings in the use of a one inch soil moisture retention value. First, in considering the lake storage⁸ and the slightly greater proportion of bog and swamp area in the Yellowknife River basin as compared to that of Pocket Lake basin, the writer believes that the average retention capacity for the general Area should be higher than the calculated value for the Pocket Lake basin. Secondly, using a single value for retention storage does not allow the identification of the variety of storage conditions, and thus, the variations of the water balance components, that actually do occur within the Area. The more refined water balance relationships based on different soil moisture retention capacities (plus variations of several other components) will be considered in detail later in this chapter.

The value of using a set soil moisture retention capacity of one inch in calculating the water balance lies in that the derived runoff figures can be easily compared with the measured discharge figures in an attempt to determine similar trends and relationships. The comparison was made by means of statistical correlations. It should be noted, however, that the use of a set retention storage capacity is an

⁸Note that Map 2-5 (chapter II) portrayed spring lake retention storage capacity as zero, and runoff was considered to be the addition of water to Pocket Lake.

unadjusted and selected application of the Thornthwaite procedure for calculating the water balance.

For mean monthly temperatures below 30.2° F. (-1° C), precipitation was considered to be in the form of snow, and the storage of moisture was allowed to exceed the soil moisture retention capacity since the snow would remain on top of the ground surface.⁹ This detained snow which accumulated throughout the winter was considered to be converted to water in the month when mean monthly temperatures first reached or exceeded 30.2° F. All of the snow in detention storage in excess of retention capacities was considered to be surplus moisture and not available for evapotranspiration or secondary soil moisture recharge within this first warm month. That is, the snow melted and was excess moisture in the first part of the month and, if the temperatures were high enough, some of the soil moisture retention storage was consumed by evapotranspiration in the latter part of the month. Therefore, the result may be the occurrence of runoff in this first warm month along with moisture withdrawal from soil moisture storage, possibly to the extent that a deficit would occur.

Because of the importance of potential evapotranspiration estimates to the calculation of the climatic water balance, it is helpful to have some measure of accuracy for this variable. The Yellowknife Airport meteorological station

⁹ Thornthwaite and Mather, Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance, p. 191.

recently began to measure evaporation from a Class A pan with the first published data appearing in the Monthly Record for July, 1966. The 1966 and 1967 measurements and adjustments to "lake evaporation" are presented in Table IV-2 along with the appropriate monthly values of calculated estimates of potential evapotranspiration using the Thornthwaite procedure.

If some allowance is made for June, 1966, the month just prior to first publication of data during which some evaporation must have occurred (maybe some 5.00 inches of lake evaporation), the seasonal totals of lake evaporation and estimated potential evapotranspiration by the Thornthwaite method are reasonably close, with lake evaporation being somewhat greater. Within each season, the estimates by the Thornthwaite procedure indicate larger monthly potential evapotranspiration at the beginning and close of the "summer" season than do the calculated lake evaporation values. However, the estimates are definitely lower than the calculated values for lake evaporation during the mid-summer months. Thus, the values estimated by the Thornthwaite procedure exhibit less variance throughout the season.

On the basis of this data, there is no reason to suggest that the estimates of seasonal potential evapotranspiration by the Thornthwaite method are greatly in error for the Yellowknife Area, however the seasonal regime is more suspect. Two other studies, both of which were conducted at Norman Wells, N.W.T., were made of the measurement of potential

TABLE IV-2

CLASS A PAN EVAPORATION DATA FOR YELLOWKNIFE AIRPORT*

Period	Total net water loss from Pan, in.	Average Wind Mile- age	Daily Water Temp. °F	Values: Air Temp. °F	Total calcu- lated lake evapo., in.**	Estimated PE by Thornthwaite procedure, in.
1966:						
May	No Data					1.94
June	No Data				(?)	4.28
July	8.91	140	63	61	6.43	4.91
Aug.	7.11	136	59	58	5.10	4.00
Sept.	2.59	122	48	47	1.88	2.15
Total					13.41	17.18
1967:						
May	-	-	-	-	-	1.00
June	7.65	154	54	51	5.64	3.32
July	8.08	145	62	60	5.76	4.74
Aug.	7.45	148	59	58	5.27	4.15
Sept.	3.32	140	48	49	2.28	2.31
Total					18.95	15.52

* Source: Canada, Department of Transport, Meteorological Branch, Monthly Record (Ottawa: Queen's Printer and Controller of Stationery, appropriate months in 1966 and 1967).

** As described in each Monthly Record: "EVAPORATION - In this table, the total monthly water losses from U. S. Weather Bureau Class A pans are given. These are sums of daily observations from tanks 4 feet in diameter, 10 inches deep, exposed above ground. Other data included are monthly averages of daily observations of wind mileage at the level of the pan rim (1 foot), and of mean pan water and air temperatures obtained from maximum and minimum thermometers in the water and in a nearby Stevenson screen. Total calculated lake evaporation is the sum of daily values computed from the observed data by the method of Kohler, Nordenson and Fox (U.S. Weather Bureau Research Paper No. 38)."

evapotranspiration near the Yellowknife Area. M. Sanderson concluded that:

The first season's results from the two evapotranspirometers at 65° N. seem to indicate that extrapolation poleward in the use of the Thornthwaite formula gives results of the right order of magnitude, in spite of the fact that the length-of-day correction factor for 50° N. latitude is used empirically for all stations farther north. Although the daily measured potential evapotranspiration does not always agree with the computed value, the totals for the season are almost the same.¹⁰

More recently, R. J. E. Brown wrote:

In conclusion, it has been stated that meteorological factors play a prominent role in evapotranspiration rates where soil moisture is not the limiting factor. Nevertheless, it is possible that the physiological characteristics, and radiational and thermal properties of such plant materials as moss and lichen, which maintain a high permafrost table, are significant factors in determining the contribution of evapotranspiration to the energy exchange of permafrost.¹¹

Therefore, estimates of potential evapotranspiration rates by the Thornthwaite procedure may well be in order generally for potential moisture use, but the unique northern plant cover may be transpiring moisture according to distinct relationships. Some variance of potential evapotranspiration seasonally and for specific site conditions will be presented later in this chapter in connection with the more detailed considerations of the water balance conditions.

¹⁰ M. Sanderson, "Measuring Potential Evapotranspiration at Norman Wells, 1949," Geographical Review, Vol. 40, No. 4 (October, 1950), p. 645.

¹¹ R. J. E. Brown, "Potential Evapotranspiration and Evaporation Observations at Norman Wells, N.W.T.," Proceedings of Hydrology Symposium No. 2: Evaporation (Ottawa: Queen's Printer and Controller of Stationery, 1965), p. 125.

Data And Correlation With Discharge

The annual (water year) water balances calculated by the Thornthwaite method and using a one inch soil moisture retention capacity are presented in Table IV-3. It is interesting to note the relative lack of variability in the potential evapotranspiration values estimated by the Thornthwaite method (standard deviation = $s = 1.041$) as compared with the annual fluctuations of precipitation ($s = 2.620$), runoff ($s = 1.860$), and deficit ($s = 1.768$). Also, the long-term mean annual deficit for the Yellowknife Airport, as calculated by the Thornthwaite procedure, exceeds the mean annual precipitation.

As a statistical measure of the amount of agreement that existed between the annual water year values of measured discharge from the Yellowknife River (X_1) and the calculated runoff using the Thornthwaite climatic water balance method (X_2), a simple correlation coefficient was calculated. Although the twenty-five year mean values were reasonably close,¹² the correlation coefficient of the two variables (.160)¹³ suggests that they do not vary in the same manner.

¹²As noted previously, the mean measured discharge in inches of depth over the drainage area equaled 3.03 inches, and calculated runoff, using the Thornthwaite method with a one inch soil moisture retention capacity, equaled 3.81 inches.

¹³The correlation coefficient at the 1 per cent level of statistical significance for these twenty-five years of data (D.F. = 23) is .505; at the 5 per cent level it is .396.

TABLE IV-3

CALCULATED WATER BALANCE BY WATER YEARS FOR YELLOWKNIFE
AIRPORT USING THORNTHWAITE PROCEDURE*

Water Year:	Ppt.	=	(PE - D)	+	Run- off	+	SC**
1942-43	11.04	=	(15.62 - 10.32)	+	5.42	+	.32
43-44	7.85	=	(17.28 - 10.53)	+	1.36	-	.26
44-45	7.89	=	(15.08 - 9.99)	+	2.71	+	.09
45-46	8.00	=	(15.91 - 12.13)	+	4.16	+	.06
46-47	7.49	=	(14.25 - 10.60)	+	3.84	+	0
47-48	10.59	=	(17.57 - 8.04)	+	1.22	-	.16
48-49	6.21	=	(15.77 - 11.54)	+	1.92	+	.06
49-50	8.54	=	(16.20 - 10.52)	+	2.81	+	.05
50-51	8.22	=	(16.30 - 10.18)	+	2.15	-	.05
51-52	10.94	=	(16.78 - 9.50)	+	3.01	+	.65
52-53	8.31	=	(16.81 - 10.42)	+	2.56	-	.64
53-54	9.66	=	(17.04 - 10.40)	+	2.97	+	.05
54-55	8.10	=	(17.11 - 12.82)	+	3.77	+	.04
55-56	8.39	=	(15.88 - 9.85)	+	2.44	-	.08
56-57	13.89	=	(15.68 - 6.91)	+	5.01	+	.11
57-58	14.81	=	(16.67 - 7.46)	+	5.08	+	.52
58-59	14.60	=	(13.18 - 6.24)	+	8.02	-	.36
59-60	13.70	=	(16.74 - 9.61)	+	6.60	-	.03
60-61	13.60	=	(16.22 - 10.70)	+	7.86	+	.22
61-62	11.12	=	(15.74 - 10.13)	+	5.79	-	.28
62-63	9.90	=	(17.12 - 10.19)	+	3.12	-	.15
63-64	7.00	=	(17.56 - 13.25)	+	2.32	+	.37
64-65	6.77	=	(15.50 - 10.94)	+	2.62	-	.41
65-66	9.79	=	(17.28 - 12.58)	+	4.93	+	.16
66-67	6.98	=	(15.52 - 12.10)	+	3.64	-	.08
Total	243.39	=	(404.81 - 256.95)	+	95.33	+	.20
Mean	9.74	=	(16.19 - 10.28)	+	3.81	+	.01

* Explanation of symbols: Ppt. = precipitation, PE = potential evapotranspiration, D = deficit, Runoff = runoff, SC = storage change. All quantities are expressed in inches.

** A one inch soil moisture storage capacity was used.
Note: Recorded Ppt. and calculated PE are to the nearest 100th of an inch, therefore the other derived values have been carried to two decimal places. It should not be assumed, however, that the derived values approximate reality with such precision.

In fact, a higher (but still insignificant) correlation existed between mean annual water year precipitation (X_3) and measured discharge (.245).¹⁴

Additional Correlations

Through manipulation of data, other variables were developed and correlated with measured discharge from Yellowknife River (X_1) in an attempt to discover possible relationships.

Twenty-five Years of Data

The writer believes that there is some delaying effect of surplus water before it is manifested as stream discharge out of the large drainage basins of the Yellowknife Area. This lag effect could be caused by the pronounced lake detention storage of water surpluses or possibly by the detention of surplus moisture in the active layer over permafrost in the low bog and muskeg portions of the drainage basins.

Sanderson¹⁵ found that the level of Lake Erie varied primarily according to local basin supply rather than inflow

¹⁴An intercorrelation matrix for all the statistically correlated variables discussed in this chapter is presented in Appendix C.

¹⁵M. Sanderson, A Climatic Water Balance of the Lake Erie Basin, 1958-1963, Publications in Climatology, Vol. XIX, No. 1 (Elmer, N. J.: C. W. Thornthwaite Associates, Laboratory of Climatology, 1966), p. 47.

from the upper Great Lakes. P. E. Day¹⁶ suggested that there was a nine month delay in the changes of the level of Lake Superior from the time precipitation was received in that basin. A. Sommer and E. S. Spence found problems in explaining the timing of the late summer peak discharge within the annual streamflow regime in the Yellowknife Area. They suggested that "the annual thermal regime in the active layer of the permafrost exerts a strong control on the runoff patterns."¹⁷

In an attempt to develop a measure of delayed runoff, the calculations of moisture surplus by the Thornthwaite procedure were used, but the delaying effect of runoff produced was accentuated. In the 1957 procedure, runoff was calculated according to Thornthwaite and Mather's instructions; that is, "in areas below 1600 m if the soil is at its water holding capacity or above, 10 per cent of the water available from the melting snow will run off during the first month with temperatures above -1° C. while 50 per cent of the remainder will run off in succeeding months."¹⁸ To delay runoff further, only 10 per cent of the surplus water for any month was considered

¹⁶P. E. Day, "Precipitation in the Drainage Area of the Great Lakes 1875-1924, with discussion on the levels of the separate lakes and relation to the annual precipitation," Monthly Weather Review, Vol. 54, 1926, pp. 85-101.

¹⁷A. Sommer and E. S. Spence, "Some Runoff Patterns in a Permafrost Area of Northern Canada," The Albertan Geographer, No. 4 (April, 1968), p. 63.

¹⁸Thornthwaite and Mather, Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance, p. 194.

to actually be manifest as runoff in that month and the remainder was carried over to the next month as water surplus. The runoff thus calculated and totaled by water years for the twenty-five years of available record composed a new set of values (X_4) which was then correlated with measured discharge for the Yellowknife River (X_1). The resulting correlation coefficient was calculated to be .266, which is not significant but considerably higher than the previous value for calculated runoff by the "regular" Thornthwaite process (X_2), which was .160.

Another measure of delayed streamflow from the time of precipitation receipt was developed by the writer. A twelve month precipitation sum extending from nine months prior to the beginning of the discharge water year through the first three months of the discharge water year was calculated for the twenty-five years of data. This set of twelve month precipitation values (X_5) was then correlated with measured discharge for the water year, and a correlation coefficient of .460 was obtained. This correlation is statistically significant at the 5 per cent level, but not at the 1 per cent level.

Twenty-four Years of Data

Additional variables were developed and correlated with discharge, but because of the incomplete meteorological records published for 1942, only twenty-four years of data were valid for these variables. A sum of the precipitation

for the twelve months preceding the discharge water year (X_6) was tallied and correlated with the Yellowknife River discharge values (X_1). The resulting correlation coefficient was calculated to be .436, which is significant at the 5 per cent level, but not at the 1 per cent level. It is interesting that this correlation coefficient is slightly lower than that derived for X_5 with X_1 (.460 using twenty-five years of data, or .467 using twenty-four years of data), and suggests that the nine month delay may be more appropriate than the twelve month delay of precipitation.

Total precipitation was subdivided into winter snow and summer rain on the basis of Thornthwaite and Mather's 30.2° F. mean monthly temperature boundary. These seasonal measures of precipitation were then correlated with measured discharge (X_1).

The snow precipitation that occurred during the discharge water year (X_7) correlated poorly (.100) with the measured discharge from Yellowknife River. To express the delaying effect, snow precipitation received during the twelve months preceding the discharge water year (X_8) was also correlated with X_1 ; this correlation coefficient was even lower (.044).

Summer rain precipitation occurring during the discharge water year (X_9) correlated somewhat more closely with measured discharge (X_1), but the .203 coefficient is still statistically insignificant. Rain precipitation received during the twelve months preceding the discharge water year

(X_{10}) was calculated to have a .592 correlation coefficient with measured discharge from the Yellowknife River basin. This coefficient is the highest calculated and is statistically significant at the 1 per cent level.

Relationships Indicated

There appear to be two main relationships indicated by the preceding correlation analysis. First, there is evidence that surplus precipitation is delayed (detained) for an unusually long time period before it materializes as stream discharge from the larger drainage basins of the Yellowknife Area. Secondly, summer precipitation (rain) could be contributing a significant portion of the surplus generated in the Area. These limited correlations, however, only suggest directions for additional research at locations of similar character so that such trends might be substantiated.

The low correlations do not necessarily indicate the invalidation of the water balance approach to investigating climatic-hydrologic relationships in the Subarctic, but they do suggest that some modification of the Thornthwaite procedure for calculating it is necessary. That is, the water balance is a sound conceptual model, but it must be adjusted for the specific conditions of the Yellowknife Area. Some modifications for detailed site conditions are discussed, and values for the water balance equation are suggested in the latter portion of this chapter.

Site-Seasonal Water Balances For Pocket Lake Basin

Introduction

An improved method of examining the water balance characteristics is to investigate the variations of the components for different land surface conditions. That is, one should establish values (and thus water balance equations) for distinct snow detention-retention-evapotranspiration variations that actually occur, rather than using a single retention capacity (one inch) and considering snow and evapotranspiration to be uniform. In addition, writing non-steady-state water balances for shorter time periods (i.e., seasonal instead of annual) reveals additional information about the time when surpluses are generated from these different areas. Such modifications and adjustments have been carried out by the writer for the Pocket Lake basin, and the results are presented in the following sections of this chapter in the form of seasonal water balance equations for the various surfaces.

Site Variations

Surface conditions in the Yellowknife Area can be distinguished on the basis of their spring water retention capacities. For Pocket Lake basin, variations of spring retention capacities have been mapped. (See Map 2-5 in chapter II.) The eight classes delimited, plus a ninth class for "bog and wet muskeg" which does not occur in Pocket Lake

basin, provide a good base from which differences in water balance conditions can be discussed. These nine site conditions are described in Table IV-4 along with the mean spring water retention capacities of the sites and the percentage of Pocket Lake basin that they occupy (as calculated from Map 2-5).

TABLE IV-4

SPRING RETENTION CAPACITY FOR DIFFERENT SURFACE CONDITIONS*

Site	Description	Mean Water Retention Capacity (in.）**	Per Cent of Area of Pocket Lake Basin
A	Bare, smooth, sloping bedrock	.13	3.83
B	Rough, flat lying bedrock with lichens	.50	25.91
C	Very rough (plucked) bedrock, slightly weathered bedrock, or thin drift covered bedrock; scant vegetation	1.00	11.29
D	Thin, coarse soil on slope with light tree-bush-grass-moss vegetation	1.50	5.55
E	Tree-moss vegetation on flat to gently sloping, well drained soil	2.13	4.77
F	Moss-tree vegetation on flat, moderately well drained soil	3.00	8.33
G	Poorly drained moss covered depressions	4.00	4.10
(H)	Bog and wet muskeg (does not occur in Pocket Lake Basin)	8.00	-
I	Deep lakes	unlimited	36.22

*See discussion on page 71 and Map 2-5 on page 72.

**Again, values have been carried to two decimal places in order to maintain continuity with other water balance values.

Precipitation Adjustment

An important adjustment can first be made to precipitation in general as measured at the Yellowknife Airport meteorological station. The problems of snow gauge catch have been discussed previously, and it was concluded that gauges usually under catch the actual amount of falling snow. The areal survey of spring snow accumulation in Pocket Lake basin was an attempt to measure quantities spatially. The resulting values for 1967 were somewhat higher than the cumulative snowfall totals recorded at the Yellowknife Airport meteorological station. The writer believes that accurate measurements of areal snow accumulation are very important to the improvement of water balance relationships in the Yellowknife Area, and that such intensive spring snow surveys should definitely be continued for a number of years with the purpose of developing an accurate adjustment which could be applied to meteorological records. Although the present snow survey research is a beginning, it does not cover an extensive enough time period to establish the form and quantity of this snow adjustment. For the 1967 spring survey the adjustment was about 13 per cent more snow accumulation on the ground than measured by the gauge. This appears to be the direction of the adjustment, but the magnitude and the consistency of the magnitude for light and heavy snow accumulation years must be refined for the Area.

In a recent Soviet review article¹⁹ adjustments of mean gauged snow and rain precipitation were suggested on the basis of "observations in several hundred stations in various parts of the country." Gauge catch was found to be an underestimate of actual precipitation mainly because of the effects of wind, loss of liquid in wetting the container, and evaporation from the gauge before measurement is made. Wind is the major cause of the under catch of snow and low intensity, small drop rainfall. Considering precipitation norms, it was suggested that:

For liquid precipitation, the average correction necessary to the rain gauge reading varies between 12% and 22% (it is usually between 14% and 16%); for solid precipitation, between 20% and 100% (usually between 40% and 60%), and for annual totals between 17% and 56% (usually between 20% and 30%).²⁰

Based upon the U.S.S.R. correction factors and the writer's knowledge of the specific Yellowknife Area characteristics, it is suggested that the twenty-five year mean snow precipitation as gauged at the Yellowknife Airport meteorological station be increased by 50 per cent and that rain precipitation be increased by 15 per cent. Specifically, the twenty-five year mean annual depth of snow water equivalent would be increased from 4.00 inches (as presented in chapter III) to 6.00 inches and the mean rain precipitation

¹⁹U.S.S.R. Interdepartmental Committee for the International Hydrologic Decade, "Summary of Methods of Computation of Water Balance (for Computation of the World Water Balance)," February, 1967, 19 pp. (Mimeographed.)

²⁰Ibid., pp. 1-2.

be increased from 5.74 inches to 6.60 inches. In addition, a small allowance of say .15 of an inch should be made for depositional gains (sublimation of atmospheric water vapor on snowpack) through the winter season.²¹ The mean annual precipitation would thus be increased from 9.74 inches to 12.75 inches.

These corrected values should provide more realistic measures of the precipitation variable and improve the estimates of the Yellowknife Area water balance. Using the adjusted precipitation values, water balances can be written for each of the specific sites which were differentiated on the basis of spring soil moisture retention capacities.

With focus on the snow aspects of the water balance, special attention is directed toward the non-steady-state equations for winter (October 16 through April 30) and the spring snow melt (May 1 through May 15). Summer (May 16 through October 15) values are developed essentially from remaining quantities. Annual totals are also presented for each site. The water balances thus derived are preliminary estimates of the conditions at each site. When additional measurements of other variables become available, these estimates should be refined. As indicated previously, calculations are carried to two decimal places, but accuracy to this level is not to be inferred.

²¹This estimate of depositional gain is based mainly on rates presented by E.D. Sabo, "Evaporation From the Snow Cover in the Ergeni District;" and P.F. Idzon, "Evaporation From the Snow Surface According to Observations at Dzhanybek," both in Selected Articles on Snow and Snow Evaporation (Washington D.C.: U. S. Department of Commerce, Office of Technical Services, translated from Russian by Israel Program for Scientific Translations, 1963) pp. 18 and 23 respectively.

Site A

The mean spring retention capacity for Site A is .13 of an inch. Considering the previously mentioned adjustments to precipitation and a slightly expanded water balance formula, the seasonal water balances for Site A are suggested to be:

$$\begin{array}{lcl}
 \text{Ppt} + \text{Dep} \pm \text{SD} & = & (\text{PE} + \text{Sub} - \text{D}) + \text{Sur} \pm \text{SC} \quad (4.1) \\
 \text{(winter)} & & \\
 6.00 + .10 - 3.25 & = & (0 + .30 - 0) + 0 + 2.55 \\
 \text{(spring)} & & \\
 .25 + .05 & = & (.50 + .05 - .12) + 2.42 - 2.55 \\
 \text{(summer)} & & \\
 6.35 & = & (15.69 + 0 - 12.84) + 3.50 \pm 0
 \end{array}$$

where: Dep = deposition of water vapor onto snowpack,
 SD = snow drifting,
 Sub = sublimation of water vapor from snowpack,
 and other symbols as indicated previously.

The mean annual water balance for Site A using the compressed form of the water balance would be:

$$\begin{array}{lcl}
 \text{Ppt} & = & (\text{PE} - \text{D}) + \text{Sur} \pm \text{SC} \\
 \text{(mean annual)} \quad 9.50 & = & (16.54 - 12.96) + 5.92 \pm 0
 \end{array}$$

Of the 6.00 inch mean winter snow accumulation, 3.25 inches are removed from Site A by drifting. Most (2.55 inches) of the remaining snow collected and exceeded the retention storage capacity as the detained snowpack because there is no potential evaporation or runoff during the winter months. There are, however, sublimational losses (estimated to be .30 of an inch) during the winter which are only partially compensated for by depositional gains (estimated to be .10 of an inch, much of which probably occurs very early in

the winter).²² These sublimation-deposition estimates are applied to all of the sites.

During the spring snow melt period sublimation is considered to be compensated for by depositional gains (.05 of an inch). The thawing temperatures convert the snowpack into water, part of which fills the retention storage, but most of which is surplus to the area. Even the meager potential evapotranspirational demands (.50 of an inch) consume all of the spring precipitation (.25 of an inch) and the retention water (.13 of an inch) so that a slight spring deficit occurs (.12 of an inch).

The 6.35 inches of summer rain contribute a moderate amount of summer runoff (3.50 inches) because of the very low retention capacity of Site A. With 15.69 inches of potential evapotranspirational demand, high deficits result on these surfaces. The mean annual water balance for Site A is the total of the precipitation factors which must be equaled by

²²These estimates are suggested in consideration of the widely divergent rates presented by Sabo, "Evaporation From the Snow Cover in the Ergeni District," p. 18; P. F. Idzon, "Evaporation From the Snow Surface According to Observations at Dzhavybek," p. 23; N. A. Masienko, G. V. Pavlenko, Yu. V. Khudomyasova, "Evaporation From the Surface of a Snow Cover Under Steppe Conditions of West Siberia," Selected Articles on Snow and Snow Evaporation (Washington, D. C.: U. S. Department of Commerce, Office of Technical Services, translated from Russian by Israel Program for Scientific Translations, 1963), p. 28; W. L. Pelton, "The Use of Lysimetric Methods to Measure Evapotranspiration," Proceedings of Hydrology Symposium No. 2: Evaporation (Ottawa: Queen's Printer and Controller of Stationery, 1965), p. 111; and W. U. Garstka, "Snow and Snow Survey," Handbook of Applied Hydrology (New York: McGraw-Hill Book Company, 1964), sec. 10, p. 30.

the total of the potential evapotranspirational and sublimational demands minus deficit plus surplus.

Site B

For the .50 of an inch retention capacity of Site B, the seasonal water balances are:

$$\begin{array}{lcl}
 \text{(winter)} & & \\
 6.00 + .10 - .50 & = & (0 + .30 - 0) + 0 + 5.30 \\
 \text{(spring)} & & \\
 .25 + .05 & = & (.50 + .05 - 0) + 4.80 - 5.05 \\
 \text{(summer)} & & \\
 6.35 & = & (15.69 + 0 - 12.09) + 3.00 - .25 \\
 \text{(mean annual)} & & \\
 12.25 & = & (16.54 - 12.09) + 7.80 \pm 0
 \end{array}$$

With less snow drifting loss (.50 of an inch) Site B detains a greater quantity of the snowpack. Although the retention capacity is slightly higher for Site B than A, the larger snowpack value provides a greater quantity of snow melt surplus in spring. Water retention is sufficient on Site B to avert a spring deficit. Surpluses from summer rains are moderate, but less in quantity than the snow melt surplus.

Site C

With a mean water retention capacity of 1.00 inch, the seasonal water balances for Site C are:

$$\begin{array}{lcl}
 \text{(winter)} & & \\
 6.00 + .10 + 2.00 & = & (0 + .30 - 0) + 0 + 7.80 \\
 \text{(spring)} & & \\
 .25 + .05 & = & (.50 + .05 - 0) + 6.80 - 7.05 \\
 \text{(summer)} & & \\
 6.35 & = & (15.69 + 0 - 9.59) + 1.00 - .75 \\
 \text{(mean annual)} & & \\
 14.75 & = & (16.54 - 9.59) + 7.80 \pm 0
 \end{array}$$

Site C is a snowdrift accumulation area receiving 2.00 extra inches of effective precipitation from surrounding surfaces (mostly Sites A and B) during the winter. Most of this snow cover is converted in spring from detention storage to snow melt generated surplus. Site C has a larger retention capacity than the previous sites; thus, more of the summer precipitation is evaporated or transpired, with only a minor amount of summer surplus being generated.

It is interesting to note that even though only spring retention capacities are considered in the present study, consideration of maximum retention capacities would not significantly alter the relationships presented here. Maximum retention values would only affect the summer surplus values, and summer surpluses are suggested to occur from only Sites A, B, and C. These three sites are primarily composed of bedrock surfaces, and the retention capacity of bedrock would not vary significantly from spring through the summer season. Therefore, the retention capacity of the significant surfaces does not vary appreciably from that considered here.

Site D

Site D has a mean water retention capacity of 1.50 inches. The seasonal water balances for this site are:

(winter)							
6.00	+	.10	+	2.00	=	(0	+ .30 - 0)
						+ 0	+ 7.80
(spring)							
.25	+	.05			=	(.25	+ .05 - 0)
						+ 6.30	- 6.30
(summer)							
6.35					=	(15.94	+ 0 - 8.09)
						+ 0	- 1.50
(mean annual)							
14.75					=	(16.54	- 8.09)
						+ 6.30	± 0

The additional precipitation gained by snow drifting is again detained through the winter, and the quantity exceeding the retention capacity is manifested as water surplus during the spring melt. A slightly reduced quantity of spring potential evapotranspiration (.25 of an inch) is considered for Site D because the shade from the tree-bush vegetational cover tends to retard the rate of snowbank melt and evapotranspiration in spring. This lower spring rate of potential evapotranspiration is probably compensated for during the summer because of the dark color of the vegetation, and thus the greater absorption of solar radiation as compared to the lighter colored bedrock outcrops. The rate of potential evapotranspiration for different surface conditions is one factor that deserves further research so that water balance relationships (especially through the summer season) can be refined.

Deficits and water surpluses are significantly less for Site D than for the previously discussed sites. This is caused by the greater retention capacity of Site D which reduces the surplus from snow melt and also eliminates surplus from summer rains. Thus, a significantly larger proportion of the moisture input to Site D is manifested as evapotranspirational output than for the previous sites. This water balance situation may have some relationship to the development of the more luxuriant vegetational cover.

Site E

The mean spring water retention capacity for Site E is 2.13 inches and the seasonal water balances for this site are:

$$\begin{array}{lcl}
 \text{(winter)} & & \\
 6.00 + .10 + 1.50 & = & (0 + .30 - 0) + 0 + 7.30 \\
 \text{(spring)} & & \\
 .25 + .05 & = & (.25 + .05 - 0) + 5.17 - 5.17 \\
 \text{(summer)} & & \\
 6.35 & = & (15.94 + 0 - 7.46) + 0 - 2.13 \\
 \text{(mean annual)} & & \\
 14.25 & = & (16.54 - 7.46) + 5.17 \pm 0
 \end{array}$$

The slight reduction of spring potential evapotranspiration is again suggested because of the vegetational shade provided for the drifted snow. With the larger retention capacity and slightly lower snowdrift addition than the previous site (D), the surplus and deficit are both decreased.

Site F

For the 3.00 inch retention capacity of Site F the seasonal water balances are:

$$\begin{array}{lcl}
 \text{(winter)} & & \\
 6.00 + .10 + .50 & = & (0 + .30 - 0) + 0 + 6.30 \\
 \text{(spring)} & & \\
 .25 + .05 & = & (.50 + .05 - 0) + 3.05 - 3.30 \\
 \text{(summer)} & & \\
 6.35 & = & (15.69 + 0 - 6.34) + 0 - 3.00 \\
 \text{(mean annual)} & & \\
 13.25 & = & (16.54 - 6.34) + 3.05 \pm 0
 \end{array}$$

Because of the smaller addition of blown snow in winter and the dominance of low growing vegetation, the spring potential evapotranspiration rate for Site F is considered to be more rapid than for the two previous sites (D and E). In fact, it is possible that the low, dark vegetation cover of

Site F could cause high total summer potential evapotranspiration rates because of slightly warmer temperatures than other surfaces. As indicated previously, such possibilities have not been considered in the present study because of the lack of published material pertinent to the problem and because the present research has been focused on snow-water supply relationships.

Site G

Site G has a 4.00 inch mean spring water retention capacity. The seasonal water balances are:

(winter)							
6.00 + .10 - 2.00 =	(0	+ .30 - 0)	+ 0 + 4.00 -	[ISR=.20]			
(spring)							
.25 + .05	= (.50	+ .05 - 0)	+ 0 - .25				
(summer)							
6.35	= (15.69 + 0	- 5.79) + 0 - 3.55					
(mean annual)							
10.75	= (16.54	- 5.79) + 0 ± 0					

The flat, moss covered depressions of Site G tend to lose snow precipitation by drifting (-2.00 inches) during the winter. Most of this snow loss drifts onto the E and F type sites, but a portion also accumulates on D sites.

The drifting loss and high water retention capacity of Site G caused a small quantity (.20 of an inch) of "incomplete storage recharge" (ISR) to result. As discussed in chapter III, this means that although the basin mean snow accumulation exceeds the mean basin retention capacity, some specific surfaces (i.e., Site G) do not detain enough snow to fill the spring retention capacity. Since the incomplete

storage recharge is local and caused by drifting, some other surfaces tend to generate not only more surplus because of drift additions but slightly larger total quantities than the basin mean values would indicate. This slight increase to water surplus must equal the amount of incomplete storage recharge. The area weighted value of ISR for Pocket Lake basin using the site-seasonal water balance equations (i.e., the .20 of an inch ISR for Site G which makes up 4.10 per cent of Pocket Lake basin) equals .0082 of an inch or a "trace." This corresponds with the trace calculated from the Generalized Surplus Map (Map 3-7 series) presented in chapter III.

The high retention capacity and lower snow accumulation of Site G also resulted in no spring or summer surplus and a slightly reduced deficit (when compared to the previous site).

Site H

Although the conditions of Site H do not occur in Pocket Lake basin, they are prevalent within the Yellowknife Area. Considering the 8.00 inches of water retention capacity, seasonal water balances have been suggested for Site H and they are:

(winter)			
6.00 + .10 ± 0	= (0	+ .30 - 0)	+ 0 + 5.80
(spring)			
.25 + .05	= (.50	+ .05 - 0)	+ 0 ± 0
(summer)			
6.35	= (15.69 + 0	- 3.79)	+ 0 - 5.80
(mean annual)			
12.75	= (16.54	- 3.79)	+ 0 ± 0

No net snow drifting is suggested for Site H. The snow that does accumulate is retained after melt and supplies part of the evapotranspirational demand. Summer rain precipitation is also totally evaporated or transpired with only a small deficit occurring.

Site I

Site I is the surface of Pocket Lake and is considered to have an unlimited water retention capacity. The seasonal water balances for the Lake surface are:

(winter)		
6.00 + .10 - .30 =	(0 + .30 - 0) + 0 + 5.50	
(spring)		
.25 + .05 =	(.25 + .05 - 0) + 0 ± 0	
(summer)		
6.35 =	(14.44 + 0 - 0) + 0 - (5.50 + 2.59)	
(mean annual)		
12.45 =	(15.04 - 0) + 0 - 2.59	

There is a slight loss of snow from the Lake surface by drifting, most of which accumulates on the surfaces of Sites C and D. The snow that is detained on the lake ice is melted in spring and provides direct addition to lake storage.

The Lake surface is slow to heat in spring for two reasons. First, in addition to the snow cover, there is lake ice which must be melted before significant heating can occur. Secondly, once the snow and ice are melted, the low elevation of the sun in spring causes a high proportion of the incoming solar radiation to be reflected by the water surface. The result is lower potential evaporation rates in

spring (.25 of an inch) than occur on most of the land surfaces.

It is believed by the writer that the lower spring rates of potential evaporation are not compensated for during the summer months, but that the air layer over deep lakes (e.g., Pocket Lake) tends to have a slightly cooler thermal regime than adjacent land surfaces. This would mainly be caused by the "marine" effect of deep water bodies and the short summer heating period in the Yellowknife Area. Thus, it is suggested that the mean annual potential evaporation is 1.50 inches less over Pocket Lake than the potential evapotranspiration for the land surfaces.

Certainly no deficit would occur for Site I, and thus, the potential evaporation demand must be equaled by a supply of water. Snow and rain contribute the major portion of the evaporational demand but not all of it. To suggest a maintenance of lake levels, some additional input source of water must be considered. This is, of course, runoff from adjacent surfaces. In considering the mean annual water balance for just the Lake surface (Site I), riparian runoff is indicated by a negative storage value (-2.59 inches).

Area Weighted Mean Annual Water Balance

To calculate a mean water balance for the entire Pocket Lake basin based on the specific site water balances, the values for each site were multiplied by the per cent of area covered by the site. Summation of the values for each

site yields the following area weighted mean annual water balance for Pocket Lake basin:

$$\text{Ppt} = (\text{PE} - \text{D}) + \text{Sur} \pm \text{SC}$$

$$12.76 = (16.00 - 6.28) + 3.98 - .94$$

or considering riparian runoff to compensate for the negative storage change on Pocket Lake:

$$12.76 = (16.00 - 6.28) + 3.04 \pm 0$$

The area weighted mean precipitation and surplus values are virtually identical to the adjusted mean precipitation and mean measured discharge values (respectively) that were recorded in the Yellowknife Area. The estimated water balances for the specific sites were manipulated so that these values would result. In so doing, the writer believes that more accurate estimates of mean potential evapotranspiration and deficit have been determined when compared to the values calculated for the Yellowknife Area using the selected one inch retention capacity.

Conclusions

More important than the refined mean potential evapotranspiration and deficit values, however, is the information developed about surplus patterns with regard to different site conditions. The water balance model provided the information about the relationships of the climatic-hydrologic components. Using the total input (adjusted precipitation) and net output (measured discharge), considerable manipulation of values was performed on the basis of previously

presented material (especially snowdrift loss or gain of precipitation). Through these manipulations for different site conditions, quantitative information was derived about spring surpluses generated from each site. Also, those sites contributing surplus water from summer precipitation (i.e., Sites A, B, and C) were identified.

For the sites contributing summer surplus, runoff is related to the "magnitude and frequency"²³ of the precipitation events. That is, with a low but existent retention capacity, the amount of surplus generated is related to the frequency of moderately large²⁴ precipitation events.

The melt of the winter's snow accumulation, in effect, is a single precipitation event. It is the largest quantity of precipitation made available for runoff at any one short time period, but it is singular in annual occurrence. For Site A with the lowest retention capacity, the largest quantity of surplus was generated from the smaller magnitude, but more frequent summer precipitation events. Site B also contributed a large quantity of surplus water from summer rains. Because of the indicated significance of summer precipitation to stream discharge by the correlation analysis,

²³M. G. Wolman and J. P. Miller used this phrase in developing their concept of effective erosional rates in their article "Magnitude and Frequency of Forces in Geomorphic Processes," The Journal of Geology, Vol. 68, No. 1 (January, 1960), pp. 54-74.

²⁴"Moderately large" is relative to the retention capacity of the site and includes those precipitation events that exceed the retention capacity.

more intensive examination of these low retention capacity sites should be conducted. According to the site-seasonal water balance equations presented, 26 per cent of the total surplus generated within Pocket Lake basin is from summer precipitation.

Another important result of considering the seasonal water balances for specific site conditions was the identification of factors that require additional investigation before further refinement of the water balance relationships can be made. One of these factors is the measurement of summer runoff from the low retention capacity surfaces. A second is measuring the quantities of water sublimated from, and deposited on the snowpack. A third is the refinement of potential evapotranspiration rates from the different site surfaces in spring and especially through the summer.

Although much of the material presented in this chapter regarding the site-seasonal water balances and also in chapter III regarding the spatial distribution of spring surpluses (especially Map 3-7) can be considered preliminary, the approaches used are believed to be sound. The spatial patterns and quantitative estimates of water supply in Pocket Lake basin provide a basis for future projects of greater areal application or intensive investigation of other components.

CHAPTER V

SUMMARY AND SUGGESTIONS FOR FUTURE RESEARCH

Summary

Water is a dynamic factor of the physical environment and highly significant to human activity. One method of assessing the quantities of water present at the land-air interface is the climatic water balance. C. W. Thornthwaite developed methods of estimating potential evapotranspiration and procedures for calculating the water balance on a monthly basis through the use of meteorological records. His techniques were developed on the basis of observations in moist, mid-latitude climates, but they are being applied generally to the entire world.

In this thesis, it was demonstrated that the annual runoff calculated by the unadjusted Thornthwaite procedure using the Yellowknife Airport meteorological data correlated poorly with the gauged discharge for the Yellowknife River. Two types of influences were suggested by the writer to be the cause of this poor relationship in the Subarctic: 1) the lack of allowance for factors characteristic to the high latitude water balance (e.g., seasonal snow cover, permafrost, large swamp, bog, and lake detention storage), and 2) the inadequate adjustment of considered variables to the high latitude conditions (e.g., maximum latitudinal adjustment of

potential evapotranspiration is to 50°). Snow cover was selected as the factor to be examined intensively in the field.

The Subarctic location of Yellowknife, N.W.T., was selected for intensive study because of the availability of meteorological data and streamflow measurements, plus its representativeness for a larger portion of northwestern Canada. For general background, pertinent factors of the Yellowknife Area physical milieu were discussed (e.g., climate, terrain, soils, and permafrost). More detailed information of the terrain and spring moisture retention capacity was presented for Pocket Lake basin where the snow surveying was conducted.

The problems of accurately measuring snow precipitation and the limitations of such point measurements were discussed. A detailed areal measure of snow depth, water equivalent, and specific gravity was made for the 1967 spring snow cover of Pocket Lake basin. The water equivalent data were presented in the form of a field evaluated, manually drawn map and also by computer maps utilizing the SYMAP program. Evaluations and comparisons were made of the maps. The water equivalents were also compared to the map of spring soil moisture retention. Spring water balance relationships were developed on the basis of three different scales:

- 1) basin means, 2) generalized units of 10,000 square feet of land surface, and 3) more detailed surface units. By subtracting the retention capacities from the spring water

equivalents, values for snow generated surpluses were derived and these data were mapped. From this analysis it was realized that with more detailed investigation some surfaces did not detain enough snow to completely replenish spring retention capacities. Because of the drifting of snow, some other surfaces detained more than would be expected and therefore, the total amount of runoff was increased slightly.

Other measures of the 1967 snow cover were presented spatially by means of SYMAPs (i.e., snow depths and specific gravities), and these distributions were discussed. A sequence of photographs illustrating the melt pattern for the entire Pocket Lake basin was examined along with photographs of selected snowbanks within the basin. Characteristics of the 1968 snow cover were presented via SYMAPs, and the patterns were compared to the previous spring data.

Through the analysis of measured annual water year discharge from the Yellowknife River (X_1) and annual water year runoff as calculated by the Thornthwaite method (X_2), a simple correlation coefficient of .160 was derived (with the 5 per cent level of statistical significance equal to .396). Other variables were correlated with measured discharge in an attempt to find factors that were more significantly related to it. An adjusted form of the Thornthwaite procedure (X_4), which expressed a delay in the manifestation of runoff from the time surplus precipitation occurred, had a better correlation but was still insignificant. Annual precipitation received during the nine months preceding, and the first three

months of, the discharge water year (X_5) correlated higher with measured discharge (significant at the 5 per cent level). The only variable that correlated higher than the 1 per cent level with measured discharge was rain precipitation (using the 30.2° F. boundary) received during the twelve months preceding the discharge water year (X_{10}).

In light of the correlation analysis and especially the relationships developed from the snow survey, numerous adjusted water balance equations were presented. Site conditions were distinguished within Pocket Lake basin on the basis of spring water retention capacities. Seasonal water balances were calculated for the winter snow accumulation period, spring melt, and summer. A mean annual water balance was calculated for each site, plus an area weighted mean annual water balance was derived for Pocket Lake basin. The major adjustment was for snowdrift gain or loss of precipitation per site, but also variations in potential evapotranspiration rates and the different retention capacities produced the water balance variations for the different surfaces.

In summation, there was a dual focus to the present study. The first was the intensive investigation of one water balance component (snow precipitation) in a Subarctic environment. The second was the analysis and adjustment of a system (the water balance) which was used to derive various climatic-hydrologic variables within this environment.

Suggestions for Future Research

Throughout this investigation of water balance factors in the Yellowknife Area, several questions have emerged which demand greater attention, and thus they are presented here as suggestions as to where further research would be most beneficial. The writer is aware that some of the following suggestions are already being investigated or are planned for study in the near future as part of the continuing International Hydrologic Decade, Baker Creek Project, however the list of suggestions includes these so that a more balanced picture may be developed.

Further work could be done on the change of various snow characteristics (e.g., water equivalent, depth, and specific gravity) throughout the melt season for different land surface conditions. The spatial variability of the specific gravity of snow cover prior to melt has received little consideration previously.

A longer record of intensive snow measurements is needed on a spatial basis to assess and refine the point measurements recorded by the northern meteorological stations. This is extremely important to any study involved with the water balance, because precipitation provides the input or initial value and the accuracy of most of the relationships is dependent upon the accuracy of the precipitation data. Once the assessment of snow precipitation has been conducted for the Yellowknife Area, a moderate number of snow sampling

sites should be selected that would give accurate index values of seasonal snow accumulation for this general region. These index sampling sites could easily be instituted in the form of a snow course, the measurements of which could be made in a short time period in the spring by whomever is available in the Area (i.e., researchers or technicians). The measurements would yield an index of snow accumulation from which total areal quantities of snow could be estimated.

With continued snow measurements, a refinement of the snowdrift-surplus generation relationships should be made. The SYMAP program could continue to aid the spatial portrayal of water balance variables. The technique of interrelating two such mapped variables for generalized areas, as it was presented in this study, and the derivation of a third variable can be an important instrument for future analysis.

From the indications that lake and active layer-permafrost detention of water surpluses from large basins exists, it is apparent that more work needs to be done in order that the processes of this relationship be understood. The annual soil moisture regime should be studied for various surficial conditions, and the rate of flow into and out of the lakes should be established. Some well designed field investigations could contribute to the understanding of these relationships. Soil moisture probes could be used to measure the quantities of water in the surficial layers of the ground at different time periods throughout the year. Experimentally, the use of artificial sprinklers could supply a known depth

of water over a homogeneous ground surface. If the amount of resulting runoff can be accurately measured, then infiltration rates and soil moisture retention capacities could be deduced. Even runoff relationships could be developed in this manner which would be similar to unit hydrograph models but artificially simulated. If refined, this would be like taking Ven Te Chow's "laboratory watershed experimental system"¹ into the field.

Another area of future research might be the improvement of the potential evapotranspiration estimates for the general Yellowknife Area and also for the variations that occur for the specific surface conditions. To accomplish this, additional measurements would be required from either lysimeters or appropriate meteorological instruments that would provide data so that potential evapotranspiration could be calculated by another approach (e.g., mass transfer, energy balance, eddy fluctuation).

With additional information on snow precipitation, detention storage, and evapotranspiration, a set of variables could be found that correlated more significantly with measured discharge. From these variables a more accurate predictor of streamflow in the Subarctic would be refined. These relationships could be further evaluated by applying

¹Ven Te Chow, Laboratory Study of Watershed Hydrology, A Contribution to the International Hydrological Decade, Civil Engineering Studies, Hydraulic Engineering Series No. 14 (Urbana, Illinois: Department of Civil Engineering, University of Illinois, September, 1967), 14 pp.

them to other similar northern Shield areas where river discharge and meteorological data are available (e.g., Snare River, Emile River, Lockhart River, Taltson River). Eventually, some of the relationships and procedures could be refined for application on a larger scale (e.g., the Mackenzie River basin) in an attempt to inventory the existing water supply for a much larger portion of northern Canada.

After the natural situations are more fully understood, some experimental modification of the physical conditions might be attempted (e.g., monomolecular films over lake and swamp surfaces). The influence of such experiments would have to be evaluated carefully; given future human demands, priorities may be such that there would have to be some modification of the "natural" physical environment in order to supply these demands. With regard to man's alteration of his physical surroundings, Thornthwaite and Mather wrote:

The three important causal factors in climate which, if influenced by man, would result in some climatic modification are solar radiation, the general circulation, and surface features. Any realistic appraisal of the ways in which man might influence the first two of these shows that such influence must be transitory and of small effect. Most of the changes man can produce on the surface features, too, result in only local or temporary climatic changes. There is, however, one significant area - the water economy - where man can significantly influence climates over large areas and on a more permanent basis.²

²C. W. Thornthwaite and J. R. Mather, The Water Balance, Publications in Climatology, Vol. VIII, No. 1 (Centerton, N. J.: Drexel Institute of Technology, Laboratory of Climatology, 1955), p. 12.

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APPENDICES

APPENDIX A

SNOW SURVEY OF POCKET LAKE BASIN*

TABLE A-1

APRIL 28-29, 1967, SNOW SAMPLES

No.	Ordinate (row) ^a	Abscissa (column) ^a	Full Tube (oz.)	Water Equiv. (in.) ^b	Snow Depth (in.)	Length of core (in.)	Specific Gravity of Snow
1	184	58	19	3	19	10	.158
2	183	64	20.5	4.5	20	12	.225
3	185	72	20	4	21.5	11	.186
4	184	77	20.5	4.5	27	10.5	.167
5	187	84	19	3	20	7	.150
6	184	81	20.5	4.5	13	8	.346
7	178	87	20	4	16	8	.250
8	176	93	19.5	3.5	11.5	9	.304
9	176	98	19.5	3.5	16	7.5	.219
10	176	104	19	3	15.5	7	.194
11	177	110	19	3	13.5	8.5	.222
12	173	114	20.5	4.5	21	12	.214
13	165	116	20	4	20	8	.200
14	161	122	21	5	25	12	.200
15	152	122	20	4	21	8	.190
16	172	60	19	3	9	6	.333
17	164	69	19	3	14	8	.214
18	159	79	19	3	13	8.5	.231
19	153	89	19.5	3.5	15	10	.233
20	147	101	19	3	11	7	.273

*A Mount Rose type snow sampler was used.

^aCoordinate on SYMAP.

^bThe weight of the empty tube plus the cradle equaled 16 ounces consistently; therefore, the "water equivalent" in inches is derived by subtracting the empty tube (16 oz.) from the "full tube" measurement.

TABLE A-1 (continued)

No.	Ordinate (row)	Abscissa (column)	Full Tube (oz.)	Water Equiv. (in.)	Snow Depth (in.)	Length of core (in.)	Specific Gravity of Snow
21	145	109	20.5	4.5	27	11.5	.167
22	143	117	20.5	4.5	23	11	.196
23	132	121	18.5	2.5	9	5	.278
24	127	113	19.5	3.5	21	7	.167
25	129	102	20.5	4.5	20.5	11.5	.220
26	127	96	22.5	6.5	24	18	.271
27	120	94	19	3	18	9	.167
28	112	92	20.5	4.5	17	13	.265
29	103	96	22.5	6.5	27	17	.241
30	105	81	18	2	8	5	.250
31	111	70	20.5	4.5	21	9.5	.214
32	115	65	21	5	25	12	.200
33	120	66	25	9	38	25	.237
34	121	64	24.5	8.5	36	21	.236
35	115	58	23.5	7.5	28	21	.268
36	105	51	20	4	16.5	9.5	.242
37	99	56	21.5	5.5	24	14	.229
38	98	73	20	4	21	9	.190
39	99	80	22.5	6.5	22	18.5	.295
40	93	87	20	4	17.5	8	.229
41	80	76	18.5	2.5	15	8	.167
42	79	65	19.5	3.5	17	8.5	.206
43	85	54	18	2	12	4.5	.167
44	79	53	20.5	4.5	22	11	.205
45	69	53	19	3	13	8	.231
46	72	60	18.5	2.5	19	6	.132
47	73	71	21	5	22	15	.227
48	74	79	20.5	4.5	19	12	.237
49	79	92	21.5	5.5	20.5	17	.268
50	90	93	19.5	3.5	18	7	.194
51	78	103	20	4	20.5	8	.195
52	71	89	20.5	4.5	19	9	.237
53	67	80	19.5	3.5	21	8	.167
54	62	70	21.5	5.5	23	14.5	.239
55	51	70	19	3	15	7	.200

TABLE A-1 (continued)

No.	Ordinate (row)	Abscissa (column)	Full Tube (oz.)	Water Equiv. (in.)	Snow Depth (in.)	Length of core (in.)	Specific Gravity of Snow
56	49	79	19	3	20	7	.150
57	54	86	23.5	7.5	24	14	.313
58	60	92	20	4	21	8	.190
59	72	94	21	5	21	14	.238
60	69	107	21	5	24	13.5	.208
61	63	106	20	4	20	13.5	.200
62	60	99	19	3	18	7	.167
63	40	101	19	3	17.5	8	.171
64	47	106	21.5	5.5	24	17.5	.229
65	38	103	19.5	3.5	17	8	.206
66	34	98	21.5	5.5	21	14	.262
67	41	86	19	3	17.5	7	.171
68	41	72	21	5	21.5	15	.233
69	37	76	21.5	5.5	23	14.5	.239
70	31	81	21	5	23	13.5	.217
71	25	93	20	4	21	8	.190
72	24	102	19.5	3.5	16.5	7	.212
73	13	99	19.5	3.5	21	8	.167
74	10	92	22.5	6.5	27	17	.241
75	14	83	20	4	18	8	.222
76	31	65	21.5	5.5	24.5	15.5	.224
77	42	63	21	5	23.5	12	.213
78	55	57	22	6	24	18	.250
79	69	44	18	2	12	6	.167
80	76	39	22	6	22	18	.273
81	86	39	20	4	22	8	.182
82	104	44	20.5	4.5	21	8.5	.214
83	107	33	21	5	22	9	.227
84	110	13	20	4	18.5	10	.216
85	127	18	23.5	7.5	26	18	.288
86	134	18	22.5	6.5	23	17	.283
87	139	17	23	7	28	15	.250
88	153	24	20	4	17	7	.235
89	160	25	19	3	17.5	7	.171
90	170	30	20.5	4.5	18	11	.250

TABLE A-1 (continued)

No.	Ordinate (row)	Abscissa (column)	Full Tube (oz.)	Water Equiv. (in.)	Snow Depth (in.)	Length of core (in.)	Specific Gravity of Snow
91	175	34	21.5	5.5	21	13	.262
92	179	40	21.5	5.5	21	15.5	.262
93	172	41	19.5	3.5	12	8	.292
94	197	54	20.5	4.5	15	9	.300
95	110	82	16	0	0	0	-
96	82	49	16	0	0	0	-
Total:				413.5	1,865.5		20.928
Mean:				4.31	19.43		.223

TABLE A-2

MAY 9-11, 1967, SNOW SAMPLES

No.	Ordinate (row) ^a	Abscissa (column) ^a	Full Tube (oz.)	Water Equiv. (in.) ^b	Snow Depth (in.)	Specific Gravity of Snow
97	179	54	17.5	1.5	3	.500
98	178	59	19	3	6	.500
99	179	60	20.5	4.5	18	.250
100	182	55	22	6	13	.461
101	184	55	21.5	5.5	20	.275
102	183	57	18.5	2.5	7	.357
103	181	58	20.5	4.5	12	.375
104	187	60	19.5	3.5	11	.318
105	187	62	19.5	3.5	14	.250
106	186	63	19.5	3.5	14	.250
107	184	68	21	5	13	.385
108	183	72	21	5	13	.385
109	187	75	18	2	6	.333
110	185	78	21	5	18	.278
111	196	77	20	4	17	.235
112	193	79	21	5	18	.278
113	189	82	19.5	3.5	12	.292
114	183	84	19	3	8	.375
115	185	85	21	5	15	.333
116	185	87	26	10	24	.417
117	179	87	19.5	3.5	10	.350
118	182	94	18	2	7	.286
119	179	95	20	4	14	.286
120	181	98	20	4	8	.500

^aCoordinates on SYMAP.

^bThe weight of the tube plus the cradle equaled 16 ounces consistently; therefore, the "water equivalent" in inches is derived by subtracting the empty tube (16 oz.) from the "full tube" measurement.

TABLE A-2 (Continued)

No.	Ordinate (row)	Abscissa (column)	Full Tube (oz.)	Water Equiv. (in.)	Snow Depth (in.)	Specific Gravity of Snow
121	183	100	18	2	5	.400
122	180	101	18	2	4.5	.444
123	183	103	18.5	2.5	10	.250
124	170	108	19	3	8	.375
125	174	109	24.5	8.5	22	.386
126	171	110	20	4	11	.364
127	177	112	21.5	5.5	17	.324
128	168	112	21.5	5.5	31	.177
129	173	116	20	4	16	.250
130	173	120	19	3	9	.333
131	167	120	18.5	2.5	8	.313
132	167	123	19.5	3.5	10	.350
133	167	125	20	4	14	.286
134	163	121	20.5	4.5	15	.300
135	161	121	20	4	15	.266
136	159	123	20	4	16	.250
137	156	125	20	4	14	.286
138	154	123	22	6	23	.261
139	154	111	22	6	15	.400
140	144	108	21	5	20	.250
141	142	108	21.5	5.5	16	.344
142	141	109	22	6	21	.286
143	136	116	25.5	9.5	31	.306
144	136	119	21.5	5.5	21	.262
145	134	119	19.5	3.5	12	.292
146	134	105	21	5	15	.333
147	136	100	21	5	18	.278
148	135	93	20.5	4.5	11	.409
149	133	93	21.5	5.5	17	.324
150	131	102	20.5	4.5	11	.409
151	128	102	21.5	5.5	18	.306
152	126	103	20	4	21	.190
153	127	116	23	7	27	.259
154	125	115	21	5	18	.278
155	123	113	19.5	3.5	9	.389

TABLE A-2 (Continued)

No.	Ordinate (row)	Abscissa (column)	Full Tube (oz.)	Water Equiv. (in.)	Snow Depth (in.)	Specific Gravity of Snow
156	122	109	20.5	4.5	17	.265
157	124	100	20	4	14	.286
158	125	87	22.5	6.5	27	.241
159	120	79	22	6	26	.231
160	116	77	21	5	25	.200
161	113	77	19.5	3.5	12	.292
162	110	75	21.5	5.5	16	.344
163	113	82	21	5	20	.250
164	115	91	20.5	4.5	18	.250
165	120	95	19.5	3.5	12	.292
166	119	96	20.5	4.5	19	.237
167	117	95	21.5	5.5	20	.275
168	117	102	21.5	5.5	21	.262
169	116	108	20	4	11	.364
170	106	104	20.5	4.5	20	.225
171	109	95	19.5	3.5	9	.389
172	107	92	23	7	21	.333
173	109	90	23	7	21	.333
174	105	80	23	7	20	.350
175	105	78	23	7.5	23	.326
176	102	76	29	13	28	.464
177	100	76	21	5	17	.294
178	100	78	23	7	19	.368
179	99	69	18.5	2.5	8	.313
180	100	65	22	6	12	.500
181	103	65	20.5	4.5	12	.375
182	104	62	20	4	8	.500
183	102	60	20	4	10	.400
184	103	58	19	3	17	.176
185	103	57	21	5	20	.250
186	111	68	19.5	3.5	13	.269
187	113	67	20.5	4.5	15	.300
188	115	65	20.5	4.5	15	.300
189	117	66	20	4	19	.211
190	119	64	22	6	35	.171

TABLE A-2 (Continued)

No.	Ordinate (row)	Abscissa (column)	Full Tube (oz.)	Water Equiv. (in.)	Snow Depth (in.)	Specific Gravity of Snow
191	110	27	16	0	0	-
192	117	60	23	7	30	.233
193	120	57	22	6	31	.194
194	118	56	23.5	7.5	32	.234
195	116	54	21	5	20	.250
196	122	54	20	4	22	.182
197	123	52	22	6	27	.222
198	126	46	20.5	4.5	22	.205
199	121	43	20	4	17	.235
200	119	42	21	5	17	.294
201	116	42	20.5	4.5	17	.265
202	114	44	20.5	4.5	17	.265
203	112	49	21	5	20	.250
204	109	43	19.5	3.5	16	.219
205	112	36	21.5	5.5	17	.324
206	123	41	21	5	18	.278
207	125	42	24	8	29	.276
208	125	40	22	6	23	.261
209	128	38	22	6	19	.316
210	135	36	20	4	11	.364
211	132	34	22.5	6.5	15	.433
212	131	34	23	7	18	.389
213	131	33	23	7	28	.250
214	131	31	21	5	17	.294
215	130	31	21	5	19	.263
216	122	28	22	6	25	.240
217	120	30	21	5	18	.278
218	116	28	22	6	25	.240
219	109	32	23.5	7.5	19	.395
220	105	32	23	7	19	.368
221	102	34	21.5	5.5	17	.324
222	99	37	18.5	2.5	9	.278
223	100	39	19.5	3.5	10	.350
224	102	41	21	5	13	.385
225	102	47	19	3	10	.300

TABLE A-2 (Continued)

No.	Ordinate (row)	Abscissa (column)	Full Tube (oz.)	Water Equiv. (in.)	Snow Depth (in.)	Specific Gravity of Snow
226	99	52	21	5	17	.294
227	96	56	21	5	22	.227
228	98	62	20	4	15	.267
229	103	88	20	4	15	.267
230	100	93	19.5	3.5	11	.318
231	99	87	19.5	3.5	11	.318
232	92	78	21	5	13	.385
233	90	72	21	5	24	.208
234	88	65	22	6	22	.273
235	89	61	20.5	4.5	19	.237
236	89	57	25	9	19	.474
237	90	52	26	10	30	.333
238	90	42	20.5	4.5	15	.300
239	94	35	21.5	5.5	18	.306
240	92	35	21	5	17	.294
241	91	37	22	6	15	.400
242	87	38	19	3	14	.214
243	88	46	20	4	12	.333
244	86	57	22	6	25	.240
245	85	69	20.5	4.5	21	.214
246	87	74	20	4	12	.333
247	84	77	21	5	17	.294
248	83	83	20	4	12	.333
249	79	81	23.5	7.5	24	.313
250	77	85	20	4	11	.364
251	75	82	21.5	5.5	19	.289
252	73	83	18.5	2.5	8	.313
253	75	80	19	3	8	.375
254	76	70	21	5	18	.278
255	80	74	22	6	17	.353
256	74	66	21.5	5.5	19	.289
257	76	60	21	5	14	.357
258	73	58	19.5	3.5	10	.350
259	72	56	22.5	6.5	21	.310
260	73	49	20.5	4.5	10	.450

TABLE A-2 (Continued)

No.	Ordinate (row)	Abscissa (column)	Full Tube (oz.)	Water Equiv. (in.)	Snow Depth (in.)	Specific Gravity of Snow
261	71	47	21.5	5.5	20	.275
262	68	49	21	5	15	.333
263	70	51	24	8	18	.444
264	68	56	22	6	21	.286
265	67	62	22	6	19	.316
266	69	66	20	4	14	.286
267	67	66	19.5	3.5	21	.167
268	66	69	20.5	4.5	17	.265
269	71	74	20.5	4.5	21	.214
270	66	73	22	6	19	.316
271	65	82	20	4	11	.364
272	64	86	20	4	12	.333
273	62	71	21	5	12	.417
274	60	68	22	6	19	.316
275	62	66	21	5	15	.333
276	56	62	20.5	4.5	14	.321
277	55	65	25	9	32	.281
278	57	70	20	4	13	.308
279	56	74	21	5	12	.417
280	56	86	22.5	6.5	23	.283
281	50	78	20.5	4.5	12	.375
282	48	81	20	4	11	.364
283	45	83	23	7	21	.333
284	45	90	18.5	2.5	10	.250
285	48	93	20	4	12	.333
286	45	96	25	9	21	.429
287	38	90	19	3	7.5	.400
288	31	92	19.5	3.5	11	.318
289	36	107	19	3	10	.300
290	32	104	22.5	6.5	22	.295
291	31	105	25	9	28	.321
292	31	107	29	13	30	.433
293	30	106	22	6	16	.375
294	26	99	21.5	5.5	18	.306
295	22	113	20	4	11	.364

TABLE A-2 (Continued)

No.	Ordinate (row)	Abscissa (column)	Full Tube (oz.)	Water Equiv. (in.)	Snow Depth (in.)	Specific Gravity of Snow
296	21	117	21	5	11	.455
297	21	123	20	4	10	.400
298	16	113	19.5	3.5	11	.318
299	17	107	18	2	7	.286
300	17	104	22	6	22	.273
301	21	99	20	4	14	.286
302	14	99	22	6	19	.316
303	12	98	22.5	6.5	22	.295
304	13	95	19.5	3.5	10	.350
305	10	93	20	4	15	.267
306	9	91	22	6	18	.333
307	8	89	20.5	4.5	16	.281
308	6	88	22.5	6.5	24	.271
309	18	82	21	5	17	.294
310	24	77	19.5	3.5	12	.292
311	28	85	19	3	10	.300
312	28	80	21	5	19	.263
313	28	78	22.5	6.5	20	.325
314	27	69	19	3	9	.333
315	31	76	21	5	12	.417
316	32	78	20	4	11	.364
317	34	78	22	6	21	.286
318	35	82	19.5	3.5	10	.350
319	43	78	20.5	4.5	16	.281
320	47	76	22	6	19	.316
321	43	72	23	7	24	.292
322	40	72	20	4	12	.333
323	34	68	21.5	5.5	17	.324
324	31	64	20	4	20	.200
325	38	63	20	4	13	.308
326	62	58	25	9	32	.281
327	63	56	23	7	23	.304
328	62	55	25	9	18	.500
329	62	53	20	4	10	.400
330	61	51	21	5	15	.333

TABLE A-2 (Continued)

No.	Ordinate (row)	Abscissa (column)	Full Tube (oz.)	Water Equiv. (in.)	Snow Depth (in.)	Specific Gravity of Snow
331	66	46	21	5	14	.357
332	73	40	21	5	18	.278
333	79	40	21	5	17	.294
334	80	32	21	5	21	.238
335	103	29	22.5	6.5	21	.310
336	110	9	20	4	16	.250
337	114	13	20	4	12	.333
338	114	16	22	6	17	.353
339	114	18	22	6	26	.231
340	117	24	22.5	6.5	25	.260
341	122	24	23.5	7.5	25	.300
342	124	21	19	3	10	.300
343	120	15	22	6	15	.400
344	121	17	20	4	10	.400
345	122	6	19	3	18	.166
346	123	13	26	10	30	.300
347	125	13	26	10	28	.280
348	129	12	24	8	22	.364
349	134	13	19.5	3.5	13	.269
350	131	18	19.5	3.5	17	.206
351	134	20	19.5	3.5	14	.250
352	131	24	20.5	4.5	18	.250
353	127	25	21.5	5.5	21	.262
354	129	27	21.5	5.5	17	.324
355	130	29	20	4	13	.308
356	137	27	23	7	16	.438
357	136	23	20	4	14	.286
358	138	21	21.5	5.5	23	.239
359	139	19	22.5	6.5	22	.295
360	141	19	22	6	17	.353
361	141	17	23	7	21	.333
362	145	15	24	8	26	.308
363	147	17	22	6	16	.375
364	149	20	22	6	26	.231
365	150	21	23	7	23	.304

TABLE A-2 (Continued)

No.	Ordinate (row)	Abcissa (column)	Full Tube (oz.)	Water Equiv. (in.)	Snow Depth (in.)	Specific Gravity of Snow
366	155	24	26	10	32	.313
367	156	24	23	7	24	.292
368	162	23	22	6	19	.316
369	162	25	19.5	3.5	10	.350
370	166	30	25	9	29	.310
371	174	35	21.5	5.5	18	.306
372	178	39	20	4	16	.250
373	180	38	19	3	17	.176
374	183	40	19	3	14	.214
375	184	42	18	2	12	.167
Total:			1415.5	4713.0	86.229	
Mean:			5.07	16.89	.310	
ALL SPRING 1967 SNOW SAMPLES (i.e., Tables A-1 and A-2 combined)						
Total:			1829.0	6578.5	107.157	
Mean:			4.87	17.54	.288	

TABLE A-3

APRIL 16-17, 1968, SNOW SAMPLES

No.	Ordinate (row) ^a	Abcissa (column) ^a	Empty Tube (oz.)	Full Tube (oz.)	Water Equiv. (in.)	Snow Depth (in.)	Specific Gravity of Snow
1	187	50	13	18	5	20	.250
2	180	48	13	16.5	3.5	14	.250
3	177	53	13	16	3	14	.214
4	174	57	13	16.5	3.5	15	.233
5	172	60	14	17	3	14	.214
6	169	65	14	17	3	13	.231
7	167	69	14	18	4	14	.286
8	164	73	14	17	3	14.5	.207
9	162	77	14	16.5	2.5	14	.179
10	159	81	14	17	3	14	.214
11	156	84	14	17	3	15	.200
12	153	88	14	13.5	1.5	15	.100
13	151	91	14	16	2	15	.133
14	148	95	13	16.5	3	15.5	.193
15	146	98	14	16.5	2.5	19	.132
16	143	101	14	19	5	26	.192
17	141	104	14	18	4	23	.174
18	138	110	14	17	3	13	.231
19	141	113	14	17	3	12	.250
20	143	117	14	19	5	28	.179
21	142	119	14	20	6	26	.231
22	148	119	15	21	6	24	.250
23	151	118	15	21	6	41	.146
24	155	115	16	20	4	15	.267
25	162	114	16	17	1	11	.091
26	163	113	16	20	4	39	.103
27	170	109	16	24	8	33	.242
28	171	102	16	19	3	22	.136
29	177	93	15	19	4	15	.267
30	178	93	15	16	1	5	.200

^aCoordinates on SYMAP.

TABLE A-3 (Continued)

No.	Ordinate (row)	Abscissa (column)	Empty Tube (oz.)	Full Tube (oz.)	Water Equiv. (in.)	Snow Depth (in.)	Specific Gravity of Snow
31	180	91	15	15.5	.5	2	.250
32	182	90	15	18	3	21	.143
33	180	88	15	23	8	21	.381
34	181	85	15	20	5	24	.208
35	180	80	15	20	5	24	.208
36	179	78	15	17	2	10.5	.190
37	186	75	15	21	6	15	.400
38	183	68	15	21	6	26	.231
39	183	61	15	22	7	26	.269
40	186	53	15	18	3	9	.333
41	186	48	13	17	4	30	.133
42	185	43	13	18	5	26	.192
43	181	39	15	18	3	26	.115
44	178	38	16	23	7	27	.259
45	175	36	14	19	5	22	.227
46	174	34	15	16	1	4	.250
47	171	31	16.5	19	2.5	13	.192
48	169	30	16.5	18	1.5	18	.083
49	168	26	16.5	23	6.5	31	.210
50	166	24	16	16	0	0	-
51	166	25	16	19	3	10	.300
52	164	26	18	24	6	26	.231
53	163	25	16.5	21.5	5	23	.217
54	160	27	15	21	6	32	.187
55	158	27	15	19	4	12	.333
56	158	25	15	19	4	19	.210
57	157	23	17	21	4	31	.129
58	157	20	16	16	0	0	-
59	156	21	15.5	22	6.5	21	.309
60	155	25	15	19.5	4.5	19	.237
61	153	24	14	18.5	4.5	19	.237
62	151	20	14	17	3	15	.200
63	148	22	16	20	4	22	.182
64	149	18	16	21	5	27	.185
65	150	18	16	21	5	28	.179

TABLE A-3 (Continued)

No.	Ordinate (row)	Abscissa (column)	Empty Tube (oz.)	Full Tube (oz.)	Water Equiv. (in.)	Snow Depth (in.)	Specific Gravity of Snow
66	146	18	15	17	2	7	.286
67	143	21	15	20	5	19	.263
68	141	22	15	25	10	38	.263
69	140	17	17	24	7	28	.250
70	138	17	17	21	4	21	.190
71	136	16	17	21.5	4.5	20	.225
72	135	14	17	22	5	25	.200
73	140	14	17	17	0	0	-
74	129	24	17	21	4	26	.154
75	126	25	15	21	6	31	.193
76	124	25	16	20	4	23	.174
77	113	10	15	18	3	13	.231
78	113	15	15	21	6	24	.250
79	116	26	17	21	4	26	.154
80	116	29	16	19	3	21	.143
81	122	32	17	21	4	24	.167
82	112	37	14	17	3	17	.176
83	110	45	14	17	3	22	.136
84	108	51	15.5	18	3.5	25	.140
85	107	56	15	17.5	2.5	19	.132
86	101	54	15.5	17.5	2	15	.133
87	97	52	17	21	4	23	.174
88	96	52	17	20	3	18	.167
89	92	46	16	19	3	20	.150
90	89	41	15	20	5	21	.238
91	84	39	15	19	4	25	.160
92	80	36	14.5	17.5	3	25	.120
93	85	50	16	16	0	0	-
94	75	43	16	18	2	25	.080
95	70	47	15	18.5	3.5	23	.152
96	68	52	15	19	4	26	.154
97	65	56	15	17	2	9	.222
98	55	61	16	18	2	20	.100
99	48	62	14	20	6	21	.286
100	42	62	14	17	3	27	.111

TABLE A-3 (Continued)

No.	Ordinate (row)	Abscissa (column)	Empty Tube (oz.)	Full Tube (oz.)	Water Equiv. (in.)	Snow Depth (in.)	Specific Gravity of Snow
101	34	70	15	20	5	24	.208
102	27	78	16	21	5	25	.200
103	22	84	15	20	5	35	.143
104	27	94	15	19.5	4.5	22	.204
105	23	110	14	18	4	23	.174
106	35	111	16	19.5	3.5	30	.117
107	33	104	15	20	5	66	.076
108	46	96	15	18	3	24	.125
109	47	89	14	17.5	3.5	22	.159
110	48	83	14	21	7	24	.292
111	52	77	14	19	5	24	.208
112	60	75	14	17	3	19	.158
113	65	75	15	22	7	27	.259
114	73	72	18	22.5	4.5	24	.187
115	80	62	18	22.5	4.5	32	.141
116	90	68	15	18.5	3.5	27	.130
117	96	72	13	16	3	15	.200
118	100	69	14	19.5	5.5	26	.211
119	105	62	14	17	3	24	.125
120	111	65	13	19	6	26	.231
121	117	62	13	17	4	17	.235
122	118	59	14	18	4	35	.114
123	120	62	14	19	5	38	.132
124	113	71	15	19	4	27	.148
125	109	75	13	21	8	29	.276
126	108	79	14.5	18	3.5	20	.175
127	113	84	15	20	5	29	.172
128	110	89	16	21	5	23	.217
129	116	92	17	21.5	4.5	24	.187
130	120	95	14	18	4	24	.166
131	127	105	15	20.5	5.5	23	.239
132	133	105	15	19	4	21	.190
133	135	103	17	19	2	18	.111
134	137	99	17	20	3	19	.158
135	136	86	15	19	4	11	.364

TABLE A-3 (Continued)

No.	Ordinate (row)	Abscissa (column)	Empty Tube (oz.)	Full Tube (oz.)	Water Equiv. (in.)	Snow Depth (in.)	Specific Gravity of Snow
136	134	74	16	18	2	11	.182
137	133	62	15	18	3	11	.273
138	133	50	15	18	3	13	.231
139	142	50	17	19.5	2.5	14	.179
140	151	50	16	19.5	3.5	14	.250
141	158	50	12	15.5	3.5	13	.269
142	166	50	12	15	3	12	.250
143	173	50	12	14	2	12	.167
144	91	53	12	12	0	0	-
Total:					562.5	2962.5	27.612
Mean:					3.906	20.573	.199

APPENDIX B

YELLOWKNIFE AREA STREAM DISCHARGE MEASUREMENTS

Description of Stream Gauging Stations

Introduction

Some discussion of the gauging mechanism, the nature of the readings, and specific comments about the conditions at each gauging station considered in this thesis is important for a more complete evaluation of the streamflow data. Much of the information is derived from the succinct descriptions of the stations which preface the recorded measurements each year in the Surface Water Data for Arctic and Western Hudson Bay Drainage and Mississippi Drainage in Canada, Water Resources Papers (Ottawa: Queen's Printer and Controller of Stationery), compiled by the Canadian Department of Energy, Mines and Resources, Water Resources Branch.¹ Also, many of the comments presented here were developed from notations appearing within the body of the streamflow data published in these Water Resources Papers. Each station is discussed separately.

¹ The precise title and name of the issuing governmental department have changed slightly a few times during the last twenty-five years, but this current title and department designation are used in all subsequent references to these Papers.

Station 7SB₂

The data for the stream gauging station on the Yellowknife River at the outlet of Prosperous Lake (station number 7SB₂) were published for only three complete water years extending from 1937 to 1940. The drainage area upstream from the gauge encompassed a larger portion of the Yellowknife River basin than did the other gauging stations on the River as it was located at the outlet of Prosperous Lake, whereas the other stations measured the flow at the inlet to Prosperous Lake.

The stream gauge at the outlet of Prosperous Lake was a staff gauge which, for most of the first two years, was read about once a week. During the winter months of 1937-38, "discharge measurements" instead of staff gauge readings were made on the River because of the ice conditions which existed from December 14, 1937 to May 28, 1938.² For this first complete year there were sixty different days in total when flow was measured, about two-thirds of which were staff gauge measurements. There was also a period from May 15 to July 5, 1938, when there was a shifting of the channel control.³

²Canada, Department of Energy, Mines and Resources, Water Resources Branch, Surface Water Data for Arctic and Western Hudson Bay Drainage and Mississippi Drainage in Canada, Water Year 1937-39, Water Resources Paper No. 84 (Ottawa: Queen's Printer and Controller of Stationery, 1942), p. 246.

³Ibid.

About the same frequency of staff reading was maintained throughout 1938-39 until September (the last month of the water year) when readings were taken almost daily. Again ice conditions existed for about three winter months.⁴

During 1939-40 measurements were apparently taken regularly; however, ice conditions were not noted. This appears to represent a policy of discontinuing such notations shortly after the station has been well established rather than the improbable condition of no ice formation.⁵ September, 1940, marked the last consecutive published record for the station. Thus, this station can be of only limited use in illustrating the long-term characteristics of streamflow or in calculating a representative mean discharge value for the Yellowknife River. Even for the three years of record the data appear only moderately reliable.

Station 7SB₅

The Yellowknife River stream gauging station located at the outlet of Bluefish Lake Dam (station number 7SB₅) was first reported for the 1941-42 water year. The records were only published through 1948-49 for this location as a separate station. The station was not abandoned, but the flow data were published only as a portion of a larger discharge

⁴Ibid.

⁵Canada, 1939-41, Water Resources Paper, No. 88, p. 271.

measurement. Beginning January 26, 1941,⁶ the discharge data for the Yellowknife River at the inlet to Prosperous Lake (station number 7SB₃) were composed of the sum of the flow past the Bluefish Lake Dam and the flow that was diverted to the Power Diversion at site Y₂ (station number 7SB₆). Therefore, the separate data for the Bluefish Dam, and also the separate records for the Power Diversion, ceased being published independently, but continued to be observed and published as a combined flow.

The Bluefish Lake Dam stream gauge is a staff type gauge which is read by the Consolidated Mining and Smelting Company's engineers. The flow past the gauge is regulated by the storage behind the dam on Bluefish Lake and by the amount of water that is diverted from Bluefish Lake to the hydro-electric power plant at the inlet of Prosperous Lake.⁷ The records for the years published separately appear to be complete and frequently observed. Ice conditions lasting for approximately three months were noted for each of the first three winter seasons.⁸ The lack of subsequent reports of ice evidently results from a change in reporting policy.

The measurements for the Bluefish Lake Dam station appear to be accurate and observed in detail for the eight

⁶Ibid., p. 268.

⁷Canada, 1945-47, Water Resources Paper No. 101, p. 364.

⁸Canada, 1939-41, Water Resources Paper No. 88, p. 226; and Canada, 1941-43, Water Resources Paper No. 92, p. 318.

published years, but their real value is their contribution to the longer, combined record of the Yellowknife River station at the inlet to Prosperous Lake (7SB₃).

Station 7SB₆

The gauging station at the Power Diversion Site Y₂ on the Yellowknife River (station number 7SB₆) was also recorded separately for the 1941-42 through 1948-49 water years. Thereafter the measurements were published as a non-differentiated portion of the Yellowknife River flow at the inlet to Prosperous Lake (station number 7SB₃).

There were a few short periods when no water was being diverted (i.e., July 25 and 26, 1941;⁹ July 2, 1943;¹⁰ and July 1, 1944¹¹), and there was a longer period of no diversion that occurred during the last days of separate publication (i.e., "plant closed down", September 7 through September 31, 1949).¹² However, it is important to note that for the vast majority of the time, the amount of water diverted for the power plant was quite consistent from month to month, and the daily diversions were only slightly less consistent. There was a small increase in total amount diverted toward the latter portion of the record.

⁹Canada, 1939-41, Water Resources Paper No. 88, p. 267.

¹⁰Canada, 1941-43, Water Resources Paper No. 92, p. 320.

¹¹Canada, 1943-45, Water Resources Paper No. 97, p. 359.

¹²Canada, 1947-49, Water Resources Paper No. 105, p. 346.

The discharge records for the Power Diversion appear accurate and frequently observed (at least daily) by the engineers of the Consolidated Mining and Smelting Company, but again, the contribution of the Power Diversion data is as an integral portion of the longer record of flow at the inlet to Prosperous Lake (7SB₃).

Station 7SB₃

The data from the Yellowknife River gauging station measuring the flow at the inlet to Prosperous Lake (station number 7SB₃) were first presented in January, 1939.¹³ It was not until the 1941-42 water year, however, that a full year's record was published. For the first three years, measurements were made by means of a staff gauge; this incomplete early record indicates a period of exploratory measurement. Therefore, these data are of very little use and have not been included in the calculations of means or totals.

The usable data begin with the 1941-42 water year.¹⁴ This is also the first year when the measurements were compiled from the combined values of flow over the Bluefish Lake Dam and the volume diverted to the power plant, and thus, the type of measurements are consistent throughout the usable record. This station is currently operating so that twenty-six years of consecutive record are available. Only the most

¹³Canada, 1937-39, Water Resources Paper No. 84, p. 247.

¹⁴Canada, 1941-43, Water Resources Paper No. 92, p. 321.

recent twenty-five years of data are used to calculate the mean annual discharge and to correlate with meteorological variables, however, because this is the available period of meteorological records.

As mentioned, the Bluefish Lake and Power Diversion flow data are considered accurate; therefore, the sum of these records, which makes up the published flow for the Yellowknife River at the inlet to Prosperous Lake, retains that accuracy. The longest continuous record is available for this station, and of course, the length of record is of considerable importance when correlating these values with other factors of the water balance.

Adjustments and Calculations of River Discharge Data

The compilations for Table IV-1 on page 205 which present discharge data for the Yellowknife River were made from the published data of the Water Resources Papers cited. There were a few slight adjustments made by the writer regarding these published values because of equivocal tallies or computations, and these adjustments are explained forthwith.

First, in summing the twelve monthly values for total acre feet discharge for the water year, a few calculated sums were slightly different from the published sum for the year. This difference is difficult to understand since it is a simple summation of presented values. Such erroneous tabulations have been omitted from Table IV-1 as far as possible,

and the correct sums of the monthly values published have been included and identified with a "d".

Examples of these summation errors are the three yearly discharge values identified by "d" for the Yellowknife River discharge at the inlet to Prosperous Lake ($7SB_3$) during the years of 1942-43, 1946-47, and 1948-49. Beginning on January 26, 1941, the published values are composed of the "sum of the flow past Bluefish Lake Dam above Prosperous Lake [$7SB_5$] and the flow diverted to the power plant at site Y_2 [$7SB_6$]." ¹⁵ First, there was an error in summing the values given for 1942-43, ¹⁶ and in all three identified years, there were errors in adding the published values for the Bluefish Lake Dam and power plant for Yellowknife River flow at the inlet to Prosperous Lake (station $7SB_3$). In two of the cases, compensating errors, or nearly compensating errors, occurred as illustrated by the water year 1948-49. The values listed for the Yellowknife River ($7SB_3$), compared with the summation values for the Dam and power plant, are presented in Table B-1. In the third case, the errors in summation were not compensating, but were compounded. The four erroneous monthly discharge totals for 1946-47 yielded a published error for the year of 130 acre feet less than the retabulated discharge (i.e., published 1946-47 year total = 524,630 acre feet for

¹⁵ Canada, 1961-62, Water Resources Paper No. 138, p. 35.

¹⁶ Canada, 1941-43, Water Resources Paper No. 92, p. 321.

Station 7SB₃ as opposed to a tabulated total = 524,760 acre feet).¹⁷

TABLE B-1

YELLOWKNIFE RIVER DISCHARGE IN ACRE FEET FOR 1948-49

Water Year 1948-49	Yk. R. at Outlet of Bluefish Dam (7SB ₄) ^a		Yk. R. Power Diversion at Site Y ₂ ^b (7SB ₆) ^{2b}		Sum of Blue- fish Dam and Power Diversion		Listed dis- charge for Yk. R. at Inlet to Prosperous Lake (7SB ₃) ^c
October	76,260	+	24,960	=	101,220	≠	101,200
November	77,630	+	23,460	=	101,090	≠	101,100
December	68,980	+	25,220	=	94,200	=	94,200
January	54,480	+	25,240	=	79,720	≠	79,700
February	33,510	+	22,620	=	56,130	=	56,130
March	25,010	+	24,680	=	49,690	=	49,690
April	16,860	+	23,200	=	40,060	=	40,060
May	26,550	+	24,560	=	51,110	≠	51,100
June	47,860	+	22,840	=	70,700	≠	70,670
July	94,550	+	24,070	=	118,620	≠	118,600
August	81,320	+	24,460	=	105,780	≠	105,900
September	61,690	+	5,110	=	66,800	≠	66,780
Year:	664,700	+	270,420	=	935,120	almost =	935,130
			(published as 270,400)				

^aCanada, 1947-49, Water Resources Paper No. 105, p. 343.

^bIbid., p. 345.

^cIbid., p. 347.

¹⁷Canada, 1945-47, Water Resources Paper No. 101, pp. 364, 366, and 368.

A second type of tabulation error in the published data was discovered when checking the figures computed for depth of runoff, in inches, from the drainage area. For some years the values were not published at all; for these years the writer divided the number of acres in the drainage basin into the annual acre foot discharge which yielded a depth of runoff in feet for the drainage area. This value was then multiplied by twelve to express it in inches of runoff and entered appropriately in Table IV-1. For the years when the inches of runoff values were published in the Water Resources Papers, the writer checked the value according to the procedure above, and in most cases identical values were reached. However, for some years slightly different runoff figures resulted. There seemed to be no consistent pattern to these differences (i.e., in the same basin, one published value might be lower than the calculated result and a subsequent year's value might be greater than the calculated amount of runoff).¹⁸ Therefore, the calculated results were used in compiling Table IV-1 and these "corrected" years are indicated by an asterisk (*).

Both of these types of tabulated errors are considered to be very minor with respect to total basin drainage and mean values, but it is hoped that the refinements discussed above have added to the accuracy of the presented data.

¹⁸For example, see: Canada, 1937-39, Water Resources Paper No. 84, p. 245.

Another potential erroneous factor of the published discharge data involves the estimation of the areas of each drainage basin. The areas were listed in the Water Resources Papers in square miles to an apparent accuracy of three significant figures. These square mile values were multiplied by 640 to convert them to acres. If the original estimate of the drainage basin area was not accurate, an erroneous depth of runoff value will result. Using overestimates of drainage basin area, the calculated depths of runoff would be lower than actually occurred and vice versa.

The water divide is the perimeter of the basin from which the area of the drainage basin is calculated. The water divide, therefore, is a very pertinent measurement to the calculation of the discharge rates for any basin. The difficulty of accurately distinguishing drainage divides in this remote area of glacially deranged drainage deserves mention, whether the approach is based on contour maps, aerial photographs, or direct field investigations.

Therefore, it is possible that the values for runoff over the basin area could be in error through inaccurate estimation of drainage basin divides. Little can be done in this thesis to evaluate this possible error, or correct for it, except to make the reader conscious that there is the possibility of a slightly erroneous area value. For a working basis, the drainage areas were used as published in all cases.

APPENDIX C

TABLE C-1

INTERCORRELATION MATRIX (N=25)*

	X ₁	X ₂	X ₃	X ₄	X ₅
X ₁	1.000				
X ₂	.160	1.000			
X ₃	.245	.756	1.000		
X ₄	.266	.824	.671	1.000	
X ₅	.460	.768	.670	.785	1.000

* Statistical significance at the .01 level with D.F. = 23 (N-2), is .505, at the .05 level it is .396.

TABLE C-2

INTERCORRELATION MATRIX (N=24)*

	X ₁	X ₃	X ₅	X ₆	X ₇	X ₈	X ₉	X ₁₀
X ₁	1.000							
X ₃	.272	1.000						
X ₅	.467	.675	1.000					
X ₆	.436	.601	.931	1.000				
X ₇	.100	.662	.655	.553	1.000			
X ₈	.044	.427	.562	.731	.374	1.000		
X ₉	.203	.714	.241	.249	-.002	.140	1.000	
X ₁₀	.592	.418	.755	.673	.404	-.013	.213	1.000

*Statistical significance at the .01 level with D.F. = 22 (N-2), is .515; at the .05 level it is .404.

Explanation of Variables

- X_1 = measured discharge, annual by water year, on Yellowknife River (station 7SB₃) in inches of depth over drainage basin;
- X_2 = runoff, annual by water year, as calculated by 1957 Thornthwaite procedure using one inch soil moisture retention capacity;
- X_3 = precipitation, mean annual by water year;
- X_4 = runoff, annual by water year, as calculated by Thornthwaite procedure but only 10 per cent of surplus runs off in each month (one inch soil moisture retention capacity);
- X_5 = precipitation, twelve months, received during the nine months preceding and through first three months of the discharge water year;
- X_6 = annual precipitation, received during the twelve months preceding the discharge water year;
- X_7 = snow precipitation (using 30.2° F. boundary) received during the discharge water year;
- X_8 = snow precipitation (using 30.2° F. boundary) received during the water year preceding the discharge water year;
- X_9 = rain precipitation (using 30.2° F. boundary) received during the discharge water year;
- X_{10} = rain precipitation (using 30.2° F. boundary) received during the water year preceding the discharge water year.

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